QuB

A Resource Aware Functional Programming Language

Apoorv Ingle

The University of Kansas

Hard problems in programming

Naming variables

Introduction and Motivation

Hard problems in programming

Resource management

in evolving production code

Resources: Files, database connections, shared mutable state

Resource Management: File Handling

- Modified File Handling API in Haskell

$$
\begin{aligned}
\texttt{openFile} &:: \texttt{FilePath} \rightarrow \texttt{IO FileHandle} \\
\texttt{closeFile} &:: \texttt{FileHandle} \rightarrow \texttt{IO} \; () \\
\texttt{readLine} &:: \texttt{FileHandle} \rightarrow \texttt{IO} \; (\texttt{String}, \texttt{FileHandle}) \\
\texttt{writeFile} &:: \texttt{String} \rightarrow \texttt{FileHandle} \\
&\qquad \rightarrow \texttt{IO FileHandle}
\end{aligned}
$$

$$
\texttt{upper} :: \texttt{String} \rightarrow \texttt{String}
$$

$$
(\gg=) :: \texttt{IO FileHandle} \rightarrow (\texttt{FileHandle} \rightarrow \texttt{IO b}) \rightarrow \texttt{IO b}
$$

- File Handling in Haskell

```
do f  ← openFile "sample.txt"
   (s, f)  ← readLine f
   let c = upper s
   f ← writeLine f c
         .
         .
         .
   () ← closeFile f
```

Resource Management: File Handling

- File Handling in Haskell Gone Wrong (Part I)

```
do f  ← openFile "sample.txt"
   (s, f)  ← readLine f
   let c = upper s
   f ← writeLine f c
         .
         .
         .
   ()  ← closeFile f
         .
         .
         .
   ()  ← closeFile f
   return c
```

Resource Management: File Handling

- File Handling in Haskell Gone Wrong (Part I)

```
do f  ← openFile "sample.txt"
   (s, f)  ← readLine f
   let c = upper s
   f ← writeLine f c
        .
        .
        .
  ()  ← closeFile f
        .
        .
        .
  ()  ← closeFile f
   return c
```

- File is closed twice: Run time crash

- File Handling in Haskell Gone Wrong (Part II)

```
do f  ← openFile "sample.txt"
   (s, f)  ← readLine f
   let c = upper s
   f ← writeLine f c
       .
       .
       .
   return c
```

Resource Management: File Handling

- File Handling in Haskell Gone Wrong (Part II)

```
do f ← openFile "sample.txt"
   (s, f) ← readLine f
   let c = upper s
   f ← writeLine f c
       .
       .
       .
   return c {- File not closed!! -}
```

- File not closed: Memory leak

Resource Management: Exception Handling

- MonadError[1] type class in Haskell

$$\begin{aligned}&\texttt{class Monad m} \Rightarrow \texttt{MonadError e m} \mid \texttt{m} \rightarrow \texttt{e where}\\ &\quad \texttt{throwError} :: \texttt{e} \rightarrow \texttt{m a}\\ &\quad \texttt{catchError} :: \texttt{m a} \rightarrow (\texttt{e} \rightarrow \texttt{m a}) \rightarrow \texttt{m a}\end{aligned}$$

- MonadError instance with IO and Exception

$$\begin{aligned}&\texttt{throwError} :: \texttt{Exception} \rightarrow \texttt{IO a}\\ &\texttt{catchError} :: \texttt{IO a} \rightarrow (\texttt{Exception} \rightarrow \texttt{IO a}) \rightarrow \texttt{IO a}\end{aligned}$$

- throwError start exception processing
- catchError exception handler

[1] Sheng Liang, Paul Hudak, and Mark Jones. 'Monad Transformers and Modular Interpreters'. In: *Proceedings of the 22Nd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*. POPL '95. New York, NY, USA: ACM, 1995, pp. 333–343

Resource Management: Exception Handling

- Using `MonadError` in Haskell

```
(do f ← openFile "sample.txt"
   (s, f) ← readLine f        {- Exception raised here -}
    let c = upper s
    () ← closeFile f
    return $ Right c)
        `catchError` (\_ →
              return $ Left "Error in reading file")
```

- Exception may cause memory leak

Well typed programs do not go wrong.

— R. Milner

Well typed programs do not go wrong.

— R. Milner

~~*Lights*~~*Types will guide you home...*

— Coldplay

Contributions

- Language design
  - Resources are "first class citizens"
  - Resources(variables) can be in sharing or separate
- QuB is logic of ***BI*** on steroids
  - Typing Environments as graphs
- Working examples
- Formalizing and proving important properties of QuB
  - Type system
  - Syntax directed type system (sound and complete)
  - Type inference algorithm $\mathcal{M}$ (sound)

Bootstrapping: STLC and $\boldsymbol{HM}$ type system

$$\lambda x.M \begin{cases} \text{Abstract over computation} \\ \text{Define functions} \end{cases}$$

$$MN \begin{cases} \text{Do the computation} \\ \text{Use functions} \end{cases}$$

Bootstrapping: STLC and *HM* type system

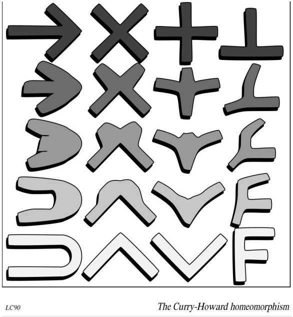
$$\lambda x.M \begin{cases} \text{Abstract over computation} \\ \text{Define functions} \end{cases} \qquad \lambda x.M : \tau \to \tau' \begin{cases} x : \tau \\ M : \tau' \end{cases}$$

$$MN \begin{cases} \text{Do the computation} \\ \text{Use functions} \end{cases} \qquad MN : \tau' \begin{cases} M : \tau \to \tau' \\ N : \tau \end{cases}$$

Bootstrapping: Curry-Howard Correspondence

HM type system ≡ Second Order Intuitionistic Propositional Logic

- Types are Propostions
- Programs are Proofs



Source: `http://lucacardelli.name/Artifacts/Drawings/CurryHoward/CurryHoward.pdf`

Bootstrapping: S O Intuitionistic Propositional Logic

$\boxed{\text{Language}}$

$$\text{Propositions and Connectives} \quad A, B, C ::= x \mid A \supset B \mid \forall x.B \mid A \vee B \mid A \wedge B$$

$$\text{Context} \quad \Gamma, \Delta ::= \epsilon \mid \Gamma, A$$

$\boxed{\text{Implicit Structural Rules}}$

$$\begin{array}{cc} A, B \vdash A \quad A, B \vdash B & \text{Contraction} \\ A \vdash A \wedge A & \text{Weakening} \\ A, B \vdash B, A & \text{Exchange} \end{array}$$

Propositions are truth values not resources

$\boxed{\text{Language}}$

Propositions and Connectives $\quad A, B, C ::= x \mid A \supset B \mid \forall x.B \mid A \vee B \mid A \wedge B$

Context $\quad \Gamma, \Delta ::= \epsilon \mid \Gamma, A$

$\boxed{\text{Implicit Structural Rules}}$

$A, B \vdash A \quad A, B \vdash B$ Contraction

$A \vdash A \wedge A$ Weakening

$A, B \vdash B, A$ Exchange

Bootstrapping: Substructural Logic

System	Who	Year	Control
Revelance Logic[2]	Orlev	1928	[WKN]
Lambek Logic[3]	Lambek	1958	[EXCH]
Affine Logic[4]	Grishin	1974	[CTR]
Linear Logic[5]	Girard	1987	[WKN] [CTR]
Logic of Bunched Implications[6]	O'Hearn and Pym	1999	[WKN] [CTR]
Separation Logic [7]	Reynolds	2002	[WKN] [CTR]
⋮	⋮	⋮	⋮

[2] Ivan Orlov. 'The Logic of Compatibility of Propositions'. In: *Matematicheskii Sbornik* (1928)

[3] Joachim Lambek. 'The Mathematics of Sentence Structure'. In: *The American Mathematical Monthly* 65.3 (1958), pp. 154–170

[4] V Grishin. 'A nonstandard logic and its application to set theory'. Russian. In: *Studies in Formalized Languages and Nonclassical Logics* (1974)

[5] Jean-Yves Girard. 'Linear logic'. In: *Theoretical Computer Science* 50.1 (1987), pp. 1–101

[6] Peter W. O'Hearn and David J. Pym. 'The Logic of Bunched Implications'. In: *The Bulletin of Symbolic Logic* 5.2 (1999), pp. 215–244

[7] John C. Reynolds. 'Separation Logic: A Logic for Shared Mutable Data Structures'. In: *Proceedings of the 17th Annual IEEE Symposium on Logic in Computer Science*. 2002

Coffee Shop

1 cup coffee costs $2

,

$\vdash$

Coffee Shop

1 cup coffee costs \$2

,

$\vdash$

,

$\nvdash$

two separate dollar bills necessary

Bootstrapping: Logic of ***BI***

- Conjunction ($\wedge$) split into two flavors

$A \otimes B$	A is separate from B
$A \mathbin{\&} B$	A is a different view of B or A shares with B

Bootstrapping: Logic of ***BI***

- Conjunction ($\wedge$) split into two flavors

$A \otimes B$	A is separate from B
$A \,\&\, B$	A is a different view of B or A shares with B

- ***BI*** contexts sensitive to different conjunction

$A, B \vdash A \otimes B$ $\qquad\qquad$ $A; B \vdash A \,\&\, B$

Bootstrapping: Logic of ***BI***

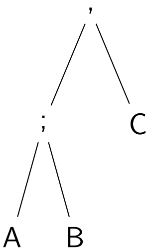
- Conjunction ($\land$) split into two flavors

$A \otimes B$	A is separate from B
$A \mathbin{\&} B$	A is a different view of B or A shares with B

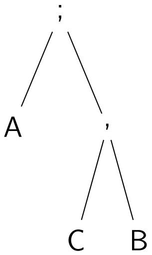
- ***BI*** contexts sensitive to different conjunction

$A, B \vdash A \otimes B$ $\qquad\qquad$ $A; B \vdash A \mathbin{\&} B$

- Contexts form trees, called bunches



$(A; B), C$



$A; (B, C)$

Bootstrapping: Logic of *BI*

Context connectives guide structural rules

- Contraction

$$A \vdash A; A$$
$$A \nvdash A, A$$

- Weakening

$$A; A \vdash A \qquad A; B \vdash B \qquad A; B \vdash A$$
$$A, B \nvdash A \qquad A, B \nvdash B$$

Coffee Shop (Revisited)

1 cup coffee costs \$2 1 cookie costs \$1

$\vdash$


$-\!\!*$


$\vdash$


$\twoheadrightarrow$


$\nvdash$


$\twoheadrightarrow$


Bootstrapping: Logic of ***BI***

Implications get corresponding flavors

$$A \otimes B \vdash C \text{ iff } A \vdash B \twoheadrightarrow C$$

$$A \,\&\, B \vdash C \text{ iff } A \vdash B \twoheadrightarrow C$$

QuB: Curry-Howard interpretation of logic of $\boldsymbol{BI}$

QuB: Types

$$\text{Types} \quad \tau, \upsilon, \phi ::= \boldsymbol{t} \mid \iota \mid \tau \to \tau$$
$$\text{where} \qquad \to \in \{\multimap, \twoheadrightarrow\}$$

- $\multimap$: Function type that is separate from its argument
- $\twoheadrightarrow$: Function type that is in sharing with its argument

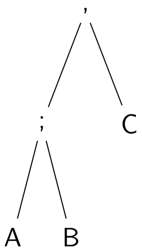
QuB: Expression Language

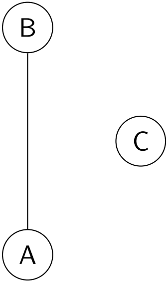
$$
\begin{aligned}
\text{Term Variables} \quad & x, y, z \in \text{Variables} \\
\text{Expressions} \quad & M, N ::= x \\
& \quad \mid \lambda^{\multimap} x.M \mid \lambda^{\twoheadrightarrow} x.M \\
& \quad \mid MN
\end{aligned}
$$

- $\lambda^{\multimap} x.M$: Argument x separate from M
- $\lambda^{\twoheadrightarrow} x.N$: Argument x sharing with M

QuB: Typing Environment

- Logic of ***BI***: Contexts are bunches
- QuB: Contexts generalized to graphs



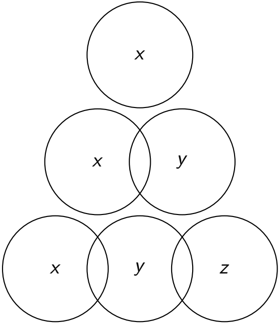


- Nodes are program objects
- (No) Edges represent (no) sharing

QuB: Typing Environment

Sharing relation Ψ

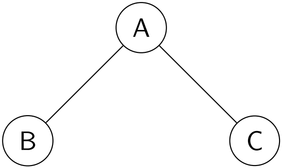
reflexive	$\forall x.\ x \,\Psi\, x$	
symmetric	$\forall x, y.\ x \,\Psi\, y \Rightarrow y \,\Psi\, x$	
non-transitive	$\forall x, y, z.\ x \,\Psi\, y \wedge y \,\Psi\, z \not\Rightarrow x \,\Psi\, z$	



- ***BI*** bunches need explicit transformations

$$A; (B, C) \equiv (A; B), (A; C)$$

- QuB sharing graphs internalize the transformation



QuB: Typing Environment

Adjacency lists for sharing graphs

"x of type σ is in sharing with $\vec{y}$"

$$(x, \sigma, \vec{y}) \in \Gamma$$

Typing Context $\quad \Gamma, \Delta ::= \epsilon \mid \Gamma, x^{\vec{y}} : \sigma$

Examples: λ-encoding standard structures

- Multiplicative Product (Separating Pair)

$$\tau \otimes \tau' = \tau \twoheadrightarrow \tau' \twoheadrightarrow (\tau \twoheadrightarrow \tau' \twoheadrightarrow \upsilon) \twoheadrightarrow \upsilon$$
$$\langle x, y \rangle = \lambda^{\twoheadrightarrow} x.\lambda^{\twoheadrightarrow} y.\lambda^{\twoheadrightarrow} f.fxy$$

- Additive Product (Sharing Pair)

$$\tau \,\&\, \tau' = \tau \twoheadrightarrow \tau' \twoheadrightarrow (\tau \twoheadrightarrow \tau' \twoheadrightarrow \upsilon) \twoheadrightarrow \upsilon$$
$$\langle x; y \rangle = \lambda^{\twoheadrightarrow} x.\lambda^{\twoheadrightarrow} y.\lambda^{\twoheadrightarrow} f.fxy$$

- Sums

$$\tau \oplus \tau' = (\tau \twoheadrightarrow \upsilon) \to (\tau' \twoheadrightarrow \upsilon) \twoheadrightarrow \upsilon$$
$$\texttt{case } c \texttt{ of } \{f; g\} = \lambda^{\twoheadrightarrow} c.\lambda^{\twoheadrightarrow} f.\lambda^{\twoheadrightarrow} g.cfg$$

$$\texttt{inl} : \tau \twoheadrightarrow (\tau \oplus \tau') \qquad \texttt{inr} : \tau' \twoheadrightarrow (\tau \oplus \tau')$$
$$\texttt{inl} = \lambda^{\twoheadrightarrow} x.\lambda^{\twoheadrightarrow} f.\lambda^{\twoheadrightarrow} g.fx \qquad \texttt{inr} = \lambda^{\twoheadrightarrow} y.\lambda^{\twoheadrightarrow} f.\lambda^{\twoheadrightarrow} g.gy$$

Towards programmer friendly

- Define custom types

$$
\begin{aligned}
&\texttt{data Bool} &&= \texttt{True} \mid \texttt{False}\\
&\texttt{data List a} &&= \texttt{Nil} \mid \texttt{Cons a a}\\
&\texttt{data Tree a} &&= \texttt{Leaf} \mid \texttt{Node a a}\\
& &&\vdots
\end{aligned}
$$

QuB: Extension

Towards programmer friendly

- Define custom types

```
data Bool   = True | False
data List a = Nil | Cons a a
data Tree a = Leaf | Node a a
              ⋮
```

- Type classes, functional dependencies

```
class Monad m a where
     return   ::  a → m a
     (>>=) :: a → (a → m b) → m b

class Collection e co | co → e where
     empty :: co
     insert :: e → co → co
     member :: e → co → Bool
            ⋮
```

More Bootstrapping: Qualified Types and Kinds

- Incorporate predicates into type language for finer grained polymorphism

$$P \mid \Gamma \vdash M : \sigma$$

- Incorporate kinds, build hierarchy over types and generalize types to type constructors[8]

$$\begin{array}{rl}
\text{Kinds} & \kappa ::= \star \mid \kappa' \to \kappa \\
\text{Types} & \tau^{\kappa}, \phi^{\kappa} ::= t^{\kappa} \mid T^{\kappa} \mid \tau^{\kappa' \to \kappa} \tau^{\kappa'} \\
\text{Type Constructors} & T^{\kappa} \in \mathcal{T}^{\kappa} \quad \text{where} \quad T^{\kappa} \subseteq \ldots
\end{array}$$

[8] Henk Barendregt. 'Introduction to generalized type systems'. In: *Journal of Functional Programming* 1.2 (1991), 125–154, Mark P. Jones. 'A System of Constructor Classes: Overloading and Implicit Higher-order Polymorphism'. In: *Proceedings of the Conference on Functional Programming Languages and Computer Architecture*. FPCA '93. New York, NY, USA: ACM, 1993, pp. 52–61

QuB: Types and Predicates

$$
\begin{array}{rl}
\text{Types} & \tau, \upsilon, \phi ::= t \mid \iota \mid \tau \to \tau \\
\text{where} & \to \in \{\overset{!}{\rightarrow\!\!\ast}, \rightarrow\!\!\ast, \overset{!}{\twoheadrightarrow}, \twoheadrightarrow\} \\
\text{Predicates} & \pi, \omega ::= \mathtt{Un}\ \tau \mid \mathtt{ShFun}\ \phi \mid \mathtt{SeFun}\ \phi
\end{array}
$$

- $\mathtt{SeFun}\ \phi$: ϕ is a function that is separate from its argument
- $\mathtt{ShFun}\ \phi$: ϕ is a function that is in sharing with its argument
- $\mathtt{Un}\ \tau$: τ does not have resources or they can be copied/dropped easily[9]

[9] J. Garrett Morris. 'The Best of Both Worlds: Linear Functional Programming Without Compromise'. In: *Proceedings of the 21st ACM SIGPLAN International Conference on Functional Programming*. ICFP 2016. New York, NY, USA: ACM, 2016, pp. 448–461

$$
\begin{array}{lrl}
\text{Types} & \tau, \upsilon, \phi ::= & t \mid \iota \mid \tau \to \tau \\
 & \text{where} & \to \in \{\overset{!}{-\!\!*}, -\!\!*, \overset{!}{\twoheadrightarrow}, \twoheadrightarrow\} \\
\text{Predicates} & \pi, \omega ::= & \mathtt{Un}\ \tau \mid \mathtt{ShFun}\ \phi \mid \mathtt{SeFun}\ \phi
\end{array}
$$

- $-\!\!*$: Function type that is separate from its argument
- $\twoheadrightarrow$: Function type that is in sharing with its argument
- $\overset{!}{-\!\!*}$, $\overset{!}{\twoheadrightarrow}$: Unrestricted versions of $-\!\!*$ and $\twoheadrightarrow$

Sharing Pair

```
data ShPair a b = ShP a; b    {- ; for sharing -}

fst :: ShPair a b ↠ a
fst (ShP a b) = a             {- Succeeds typecheck -}

snd :: ShPair a b ↠ b
snd (ShP a b) = b             {- Succeeds typecheck -}

swap :: ShPair a b ↠ ShPair b a
swap (ShP a b) = ShP b a      {- Succeeds typecheck -}
```

Separating Pair

```
data SePair a b = SeP a, b    {- , for separation -}

fst :: SePair a b -* a
fst (SeP a b) = a             {- Fails typecheck -}

snd :: SePair a b -* b
snd (SeP a b) = b             {- Fails typecheck -}

swap :: SePair a b -* SePair b a
swap (SeP a b) = SePair b a   {- Succeeds typecheck -}
```

Motivation Revisited

What about filehandles, exceptions and memory leaks and runtime crashes?

File Handling API in QuB

$$\texttt{openFile} :: \texttt{FilePath} \multimap \texttt{IO FileHandle}$$

$$\texttt{closeFile} :: \texttt{FileHandle} \multimap \texttt{IO} \ ()$$

$$\texttt{readLine} :: \texttt{FileHandle} \multimap \texttt{IO} \ (\texttt{String}, \texttt{FileHandle})$$

$$\begin{aligned}\texttt{writeFile} :: \texttt{String} &\multimap \texttt{FileHandle} \\ &\multimap \texttt{IO FileHandle}\end{aligned}$$

$$(\gg=) :: \texttt{IO a} \multimap (\texttt{a} \multimap \texttt{IO b}) \multimap \texttt{IO b}$$

Filehandles Revisited

```
do f      ← openFile "sample.txt"
   (s, f) ← readLine f
   ()     ← closeFile f
   ()     ← closeFile f
```

$\rightsquigarrow \quad \rightsquigarrow \quad \rightsquigarrow$

```
(>>=) (openFile "sample.txt") (\ f →

(>>=) (readLine f) (\ (s, f) →

(>>=) (closeFile f) (\ _ → closeFile f)
```

Filehandles Revisited

```
do f  ← openFile "sample.txt"
   (s, f)  ← readLine f
   () ← closeFile f
   () ← closeFile f
```

⇝ ⇝ ⇝

```
(>>=) (openFile "sample.txt") (\ f →

(>>=) (readLine f) (\ (s, f) →

(>>=) (closeFile f) (\ _ → closeFile f)
```

Fails Typecheck!

```
do f  ← openFile "sample.txt"
   (s, f)  ← readLine f
   ()  ← closeFile f
   ()  ← closeFile f
```

```
{- (>>=) :: IO a -* (a -* IO b) -* IO b -}
(>>=) (openFile "sample.txt") (\ f →
{- (>>=) :: IO a -* (a -* IO b) -* IO b -}
(>>=) (readLine f) (\ (s, f) →
{- (>>=) :: IO a -* (a -* IO b) ↠ IO b -}
(>>=) (closeFile f) (\ _ → closeFile f)
```

Exceptions Revisited

$$
\begin{array}{l}
\texttt{openFile} :: \texttt{FilePath} \multimap \texttt{IO FileHandle} \\
\texttt{closeFile} :: \texttt{FileHandle} \multimap \texttt{IO} \; () \\
\texttt{readFile} :: \texttt{FileHandle} \multimap \texttt{IOF} \; (\texttt{String}, \texttt{FileHandle}) \\
\texttt{writeFile} :: \texttt{String} \multimap \texttt{FileHandle} \multimap \texttt{IOF FileHandle} \\
\\
\texttt{throw} :: \; \texttt{Exception} \multimap \texttt{IOF a} \\
\texttt{catch} :: \; \texttt{IOF a} \multimap (\texttt{Exception} \multimap \texttt{IO a}) \twoheadrightarrow \texttt{IO a}
\end{array}
$$

- May not fail `IO a`
- May fail `IOF a`

Exceptions Revisited

```
readFromFile :: FilePath ⊸ IO (Either String String)
readFromFile fpath =
(do fh  ← openFile fpath
   (s, fh)  ← readLine fh
   let l = caps s
   () ← closeFile fh
   return $ Right l) `catch`
         (\e → do closeFile fh
                  return $ Left "Could not read file")
```

- Filehandle `fh` is shared between the `catch` arguments

```
catch :: IOF a ⊸ (Exception ⊸ IO a) ↠ IO a
```

- Avoids memory leak

Contributions revisited

- Language design
  - Resources are "first class citizens"
  - Resources(variables) can be in sharing or separate
- QuB is logic of ***BI*** on steroids
  - Typing Environments as graphs
- Working examples
- Formalizing and proving important properties of QuB
  - Type system
  - Syntax directed type system (sound and complete)
  - Type inference algorithm $\mathcal{M}$ (sound)

Future Work

p

- Type inference algorithm $\mathcal{M}$ is incomplete

  Terms can have two types

  - $\{\texttt{Un}\ A\} \mid \varnothing \vdash \lambda^{\multimap} f.\lambda^{\multimap} x.fxx : (A \multimap A \multimap B) \multimap A \multimap B$
  - $\varnothing \mid \varnothing \vdash \lambda^{\multimap} f.\lambda^{\multimap} x.fxx : (A \multimap A \twoheadrightarrow B) \multimap A \twoheadrightarrow B$

- Current semantics: call-by-value assumed

  Formalize resource correctness

Thank You!

Q & A

References I

Sheng Liang, Paul Hudak, and Mark Jones. 'Monad Transformers and Modular Interpreters'. In: *Proceedings of the 22Nd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*. POPL '95. New York, NY, USA: ACM, 1995, pp. 333–343.

Ivan Orlov. 'The Logic of Compatibility of Propositions'. In: *Matematicheskii Sbornik* (1928).

Joachim Lambek. 'The Mathematics of Sentence Structure'. In: *The American Mathematical Monthly* 65.3 (1958), pp. 154–170.

V Grishin. 'A nonstandard logic and its application to set theory'. Russian. In: *Studies in Formalized Languages and Nonclassical Logics* (1974).

Jean-Yves Girard. 'Linear logic'. In: *Theoretical Computer Science* 50.1 (1987), pp. 1–101.

References II

Peter W. O'Hearn and David J. Pym. 'The Logic of Bunched Implications'. In: *The Bulletin of Symbolic Logic* 5.2 (1999), pp. 215–244.

John C. Reynolds. 'Separation Logic: A Logic for Shared Mutable Data Structures'. In: *Proceedings of the 17th Annual IEEE Symposium on Logic in Computer Science*. 2002.

Henk Barendregt. 'Introduction to generalized type systems'. In: *Journal of Functional Programming* 1.2 (1991), 125–154.

Mark P. Jones. 'A System of Constructor Classes: Overloading and Implicit Higher-order Polymorphism'. In: *Proceedings of the Conference on Functional Programming Languages and Computer Architecture*. FPCA '93. New York, NY, USA: ACM, 1993, pp. 52–61.

References III

J. Garrett Morris. 'The Best of Both Worlds: Linear Functional Programming Without Compromise'. In: *Proceedings of the 21st ACM SIGPLAN International Conference on Functional Programming*. ICFP 2016. New York, NY, USA: ACM, 2016, pp. 448–461.