QuB

A Resource Aware Functional Programming Language

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Hard problems in programming

Naming variables

Hard problems in programming

Resource management

in evolving production code

Resources: Files, database connections, entity with a shared state

Resource Management: File Handling

- Modified File Handling API in Haskell

```
openFile :: FilePath  → IO FileHandle

closeFile :: FileHandle → IO ()

readLine :: FileHandle → IO (String, FileHandle)

writeFile :: String    → FileHandle
                       → IO ((), FileHandle)


upper     :: String    → String
```

Resource Management: File Handling

- 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

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
```

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`[4] in Haskell

```
class Monad m ⇒ MonadError e m | m → e where
    throwError :: e → m a
    catchError :: m a → (e → m a) → m a
```

- `throwError` starts exception processing
- `catchError` exception handler

Resource Management: Exception Handling

- Using `MonadError` in Haskell

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

- Design and implement QuB type system
  - Resources as first class citizens
  - Program objects are restricted or unrestricted
  - Functions that share resources with their arguments or are separate.
- Formalizing and proving important properties of QuB
- QuB is logic of ***BI*** on steroids
  - Typing Environments as graphs
- Working examples

Background Work: Simply Typed Lambda Calculus (STLC)

$\lambda x.M$
- Abstract over computation
- Define functions

MN
- Do the computation
- Use functions

Background Work: Simply Typed Lambda Calculus (STLC)

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

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

$$\frac{\Gamma_x, x : \tau \vdash M : \tau'}{\Gamma \vdash \lambda x.M : \tau \to \tau'} [\to \text{I}] \qquad \frac{\Gamma \vdash M : \tau \to \tau' \qquad \Gamma \vdash N : \tau}{\Gamma \vdash MN : \tau'} [\to \text{E}]$$

Background Work: Simply Typed Lambda Calculus (STLC)

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

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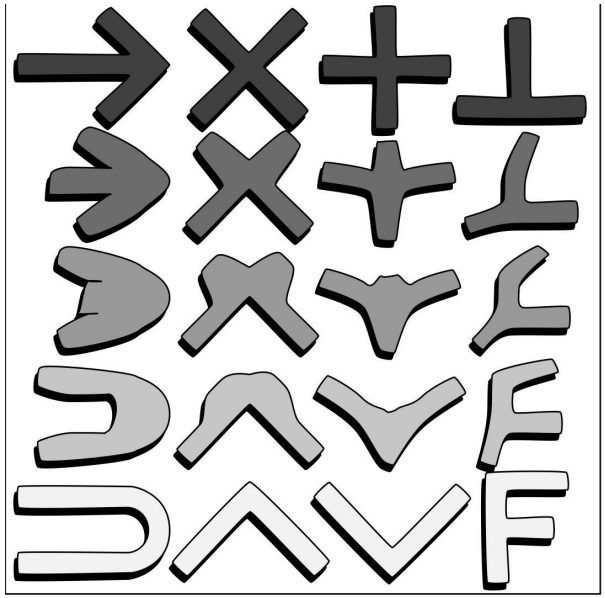
Hindley-Milner (***HM***) type system ensures sane programs

Background Work: Curry-Howard Correspondence

- Types are Propostions
- Programs are Proofs

HM type system ≡ Second Order Intuitionistic Propositional Logic



LC'90 *The Curry-Howard homeomorphism*

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

Background Work: Second Order Intuitionistic Propositional Logic

Language

Propostions & connectives $\quad A, B, C ::= x \mid A \supset B \mid \forall x.B \mid \ldots$

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

Logic Rules

$$\frac{}{A \vdash A}\ [\mathrm{Ax}]$$

$$\frac{\Gamma \vdash B \qquad x \notin \Gamma}{\forall x.B}\ [\forall \mathrm{I}] \qquad \frac{\Gamma \vdash \forall x.B \qquad \Gamma \vdash A}{B[x/A]}\ [\forall \mathrm{E}]$$

$$\frac{\Gamma, A \vdash B}{\Gamma \vdash A \supset B}\ [\supset \mathrm{I}] \qquad \frac{\Gamma \vdash A \supset B \qquad \Gamma \vdash A}{\Gamma \vdash B}\ [\supset \mathrm{E}]$$

Propositions are truth values not resources

Language

Propostions & connectives $A, B, C ::= x \mid A \supset B \mid \forall x.B \mid \ldots$

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

Logic Rules

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Background Work: Substructural Logic

- Structural rules implicit in intuitionistic propositional logics

$$\frac{\Gamma \vdash B}{\Gamma, A \vdash B}\ [\text{WKN}] \qquad \frac{\Gamma, A, A \vdash B}{\Gamma, A \vdash B}\ [\text{CTR}] \qquad \frac{\Gamma, \Delta \vdash B}{\Delta, \Gamma \vdash B}\ [\text{EXCH}]$$

Background Work: Substructural Logic

- Structural rules implicit in intuitionistic propositional logics

$$\frac{\Gamma \vdash B}{\Gamma, A \vdash B}\ [\text{WKN}] \qquad \frac{\Gamma, A, A \vdash B}{\Gamma, A \vdash B}\ [\text{CTR}] \qquad \frac{\Gamma, \Delta \vdash B}{\Delta, \Gamma \vdash B}\ [\text{EXCH}]$$

- Control the use of [WKN] and [CTR]

Propositions now behave like resources

Background Work: Substructural Logic

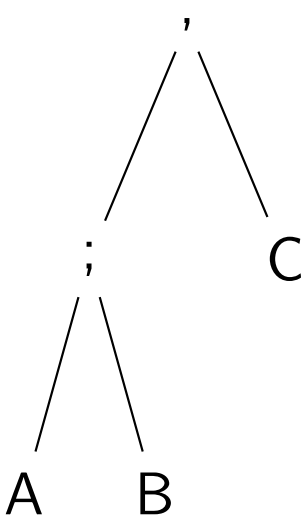
System	Who	Restrictions
Linear Logic[1]	Girard	[WKN] [CTRN]
Lambek Logic[3]	Lambek	[EXCH]
Logic of Bunched Implications[6]	O'Hearn and Pym	[WKN] [CTRN]
⋮	⋮	⋮

Background Work: Logic of Bunched Implications (***BI***)

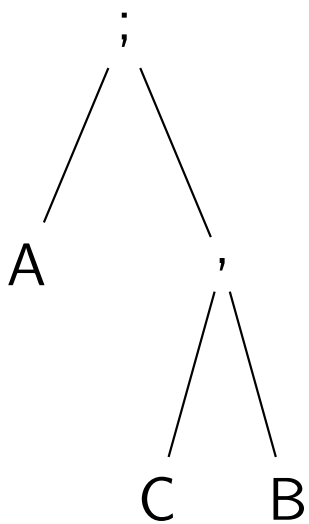
- Contexts are usually lists or sets

$$\Gamma, A, B$$

- In logic of ***BI***, contexts are trees and called are bunches
- Two connective used to combine bunches: $A; B$ or A, B



$\Gamma = (A; B), C$



$\Gamma = A; (B, C)$

Background Work: Logic of *BI*

Structural rules guided by context connectives

- Weakening

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

- Contraction

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

Interpretation:

- Propositions connected with , are separate resources
- Propositions connected with ; are sharing resources

Background Work: Logic of *BI*

(Absence of) Structural rules and logical connectives:

- Meaning of conjunction

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

- Meaning of implication

$$\frac{\Gamma, A \vdash B}{\Gamma \vdash A \mathrel{-\!\!*} B}\,[\mathrel{-\!\!*}\mathrm{I}] \qquad\qquad \frac{\Gamma; A \vdash B}{\Gamma \vdash A \twoheadrightarrow B}\,[\twoheadrightarrow\mathrm{I}]$$

Background work: Logic of *BI*

Coffee Shop

1 cup coffee costs \$2

$\otimes$

$\vdash$

Background work: Logic of *BI*

Coffee Shop

1 cup coffee costs \$2

$\otimes$

$\vdash$

$\&$

$\nvdash$

Background work: Logic of *BI*

Coffee Shop

1 cup coffee costs \$2

$\vdash$

$\twoheadrightarrow$

;

$\twoheadrightarrow$

$\not=$

Background Work: Qualified Types

$$\Gamma \vdash M : \sigma$$

"Type of M is σ
and Γ specifies the free variables in M"

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

"Type of M is σ
when predicates in P are satisfied
and Γ specifies the free variables in M"[2]

Incorporate predicates into type language for finer grained polymorphism

Background Work: Qualified Types

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

"Type of M is σ
when predicates in P are satisfied
and Γ specifies the free variables in M"[2]

Incorporate predicates into type language for finer grained polymorphism

$$(P \mid \sigma)$$

Instances of σ that satisfy P

Background Work: Quill

Quill[5]: Qualified types + linear logic

Predicates:

- `Un` τ If τ does not have resources or can be copied or dropped easily.
- `Fun` τ If τ is a function type
- $\tau \geq \tau'$ If τ less restricting than τ'

Background Work: Quill

Quill[5]: Qualified types + linear logic

Qualifying Types:

- Unrestricted Types: `Un Int`, `Un` Bool
- Restricted or Linear Types: FileHandle
- Function Types: `Fun (Int → Int)`, `Fun (String → String)`

QuB

- Quill: Qualified types + linear logic
- QuB: Qualified types + logic of bunched implications

QuB: Types and Predicates

$$\text{Types} \quad \tau, \upsilon, \phi ::= t \mid \iota \mid \tau \to \tau$$

$$\text{where} \qquad \to \in \{\overset{!}{\twoheadrightarrow}, \twoheadrightarrow, \overset{!}{\twoheadrightarrow}, \twoheadrightarrow\}$$

$$\text{Predicates} \quad \pi, \omega ::= \texttt{Un}\ \tau \mid \texttt{ShFun}\ \phi \mid \texttt{SeFun}\ \phi \mid \tau \geq \tau'$$

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

QuB: Types and Predicates

$$\text{Types} \quad \tau, \upsilon, \phi ::= t \mid \iota \mid \tau \to \tau$$

$$\text{where} \qquad \to \in \{\overset{!}{\twoheadrightarrow}, \twoheadrightarrow, \overset{!}{\Rightarrow}, \Rightarrow\}$$

$$\text{Predicates} \quad \pi, \omega ::= \texttt{Un}\ \tau \mid \texttt{ShFun}\ \phi \mid \texttt{SeFun}\ \phi \mid \tau \geq \tau'$$

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

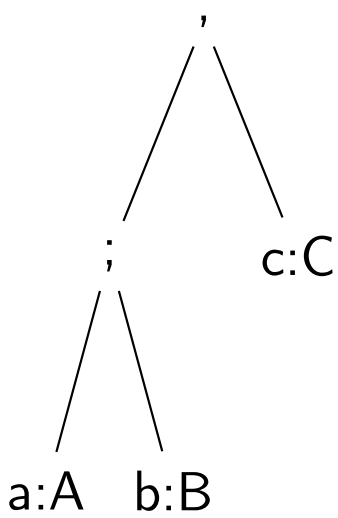
QuB: Expression Language

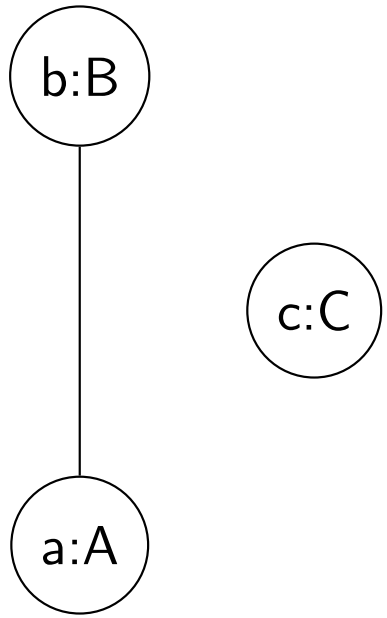
$$\begin{aligned} \text{Term Variables} \quad & x, y, z \in \text{Var} \\ \text{Expressions} \quad & M, N ::= x \\ & \mid \lambda^{\to *} x.M \mid \lambda^{\to \to} x.M \\ & \mid MN \mid \texttt{let } x = M \texttt{ in } N \end{aligned}$$

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

QuB: Typing Environment

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





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

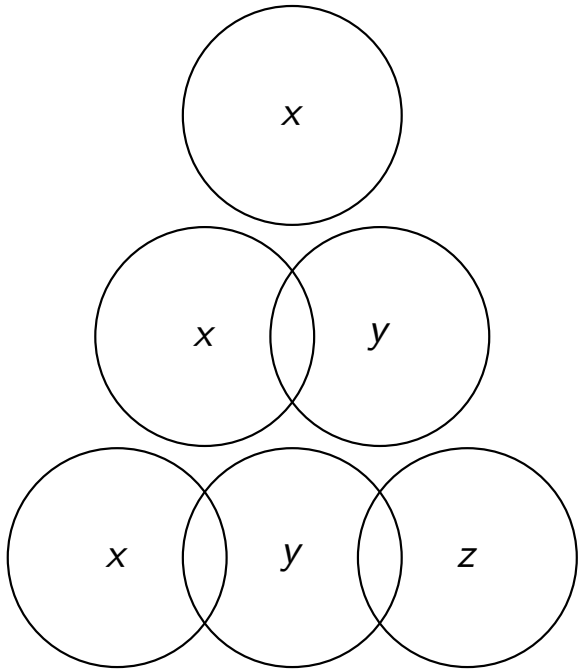
QuB: Typing Environment

Sharing relation Ψ

reflexive $\quad \forall x.\ x \,\Psi\, x$

symmetric $\quad \forall x, y.\ x \,\Psi\, y \Rightarrow y \,\Psi\, x$

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



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: Basic Data Structures

- Multiplicative Product

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

- Additive Product

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

- Sums

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

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

QuB: Extension

- User defined types and type classes
- Kind System with type constructors

$$t, u \in \text{Type Variables}$$

$$\text{Kinds} \quad \kappa ::= \star \mid \kappa' \to \kappa$$

$$\text{Types} \quad \tau^{\kappa}, \phi^{\kappa} ::= t^{\kappa} \mid T^{\kappa} \mid \tau^{\kappa' \to \kappa} \tau^{\kappa'}$$

$$\text{Type Constructors} \quad T^{\kappa} \in \mathcal{T}^{\kappa}$$

$$\text{where} \quad \{\otimes, \&, \oplus, \overset{!}{\twoheadrightarrow}, \twoheadrightarrow, \overset{!}{\to}, \to\} \subseteq \mathcal{T}^{\star \to \star \to \star}$$

$$\text{Predicates} \quad \pi, \omega ::= \texttt{Un}\ \tau \mid \texttt{SeFun}\ \phi \mid \texttt{ShFun}\ \phi \mid \tau \geq \tau'$$

QuB: Extension

- Sharing Pair

```
data ShPair a b = ShP a b

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

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

QuB: Extension

- Sharing Pair

```
data ShPair a b = ShP a b

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

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

- Separating Pair

```
data SePair a b = SeP a b

fst :: SePair a b ⇸ a
fst (SeP a b) = a                    {- 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?

Filehandles Revisited

File Handling API in QuB

```
openFile :: FilePath  -* IO FileHandle

closeFile :: FileHandle -* IO ()

readLine :: FileHandle -* IO (String, FileHandle)

writeFile :: String    -* FileHandle
                       -* IO ((), FileHandle)
```

```
(>>=) :: IO a -* (a -* IO b) -* IO b
```

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)
```

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

```
openFile :: FilePath ↛ IO FileHandle
closeFile :: FileHandle ↛ IO ()
readFile :: FileHandle ↛ IOF (String, FileHandle)
writeFile :: String ↛ FileHandle ↛ IOF ((), FileHandle)

throw :: Exception ↛ IOF a
catch :: IOF a ↛ (Exception ↛ IO a) ↠ IO a
```

- 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
- Avoids memory leak

Contributions revisited

- Design and implement QuB type system
  - Resources as first class citizens
  - Program objects are restricted or unrestricted
  - Functions that share resources with their arguments or are separate.
- Formalizing and proving important properties of QuB
- QuB is logic of ***BI*** on steroids
  - Typing Environments as graphs
- Working examples

Future Work

- Type inference algorithm $\mathcal{M}$ is incomplete. Terms can have two types.
  - $\{\texttt{Un}\ A\} \mid \varnothing \vdash \lambda^{-\!*} f.\lambda^{-\!*} x.fxx : (A \twoheadrightarrow A \twoheadrightarrow B) \twoheadrightarrow A \twoheadrightarrow B$
  - $\varnothing \mid \varnothing \vdash \lambda^{-\!*} f.\lambda^{-\!*} x.fxx : (A \twoheadrightarrow A \twoheadrightarrow B) \twoheadrightarrow A \twoheadrightarrow B$
- No formal semantic model yet

Thank You!

Q & A

References I

[1] Jean-Yves Girard. Linear logic. *Theoretical Computer Science*, 50(1):1–101, 1987.

[2] Mark P. Jones. A theory of qualified types. *Science of Computer Programming*, 22(3):231 – 256, 1994.

[3] Joachim Lambek. The mathematics of sentence structure. 65(3):154–170, 1958.

[4] 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, pages 333–343. ACM, 1995.

[5] 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, pages 448–461. ACM, 2016.

References II

[6] Peter W. O'Hearn and David J. Pym. The logic of bunched implications. *The Bulletin of Symbolic Logic*, 5(2):215–244, 1999.