Soundly Handling Linearity

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EHOP Workshop, 22th July 2023

(Joint work with Daniel Hillerström, Sam Lindley, and J. Garrett Morris)

Linear Types in LINKS

LINKS uses linear types for session types:

- `!A.S` : send a value of type `A`, then continue as `S`
- `?A.S` : receive a value of type `A`, then continue as `S`
- `End` : no communication

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Primitive operations on session-typed channels:

```
send    : forall (a::Any) (b::Session) . (a, !a.b) -> b
receive : forall (a::Any) (b::Session) . (?a.b) -> (a, b)
fork    : forall          (b::Session) . (b -> ()) -> ~b
close   : End -> ()
```

Linear Types in LINKS

A sender sends an integer.

```
sig sender       : (!Int.End) ~> ()
fun sender(ch)   { var ch' = send(42, ch); close(ch') }
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A receiver receives the integer and prints it.

```
sig receiver     : (?Int.End) ~> ()
fun receiver(ch) { var (i, ch') = receive(ch); close(ch'); printInt(i) }
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sig sender       : (!Int.End) ~> ()
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A receiver receives the integer and prints it.

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sig receiver     : (?Int.End) ~> ()
fun receiver(ch) { var (i, ch') = receive(ch); close(ch'); printInt(i) }
```

Fork the receiver and pass the dual channel to the sender.

```
links> { var ch = fork(receiver); sender(ch) };
42
```

Linear types in LINKS are sound ?

Linear channels cannot be used twice.

```
links> { var ch = fork(receiver); sender(ch); sender(ch); };
Type error: Variable ch has linear type `!Int.End'
but is used 2 times.
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Unlimited functions cannot capture linear channels.

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         var f  = fun(){ sender(ch) }; f(); f() };
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links> { var ch = fork(receiver);
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```

No, well-typed programs in LINKS can go wrong ! [1][2]

We can use the same channel twice by multi-shot handlers.

```
links> handle
       ({ var ch = fork(receiver); var _ = do Choose; sender(ch) })
       { case <Choose => r> -> r(true); r(false) }
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 chan_3 (in Hashtbl.find) while interpreting.
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We fix this by extending the linear type system and effect system to track *control flow linearity*, in addition to value linearity.

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Value Linearity in F°_{eff}

Value linearity restricts the *use* of values.

Value linearity characterises whether values contain linear resources.

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$\mathsf{F}^{\circ}_{\text{eff}}$ tracks the value linearity with kinds.

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\begin{array}{ll}
\mathit{Int} & : \mathsf{Type}^{\bullet} \\
\mathit{File} & : \mathsf{Type}^{\circ} \\
(\mathit{File}, \mathit{Int}) & : \mathsf{Type}^{\circ} \\
A \to^{\circ} C & : \mathsf{Type}^{\circ}
\end{array}
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\end{aligned}$$

Functions are annotated with their value linearity.

$$\lambda^{\bullet} f.\, (\lambda^{\circ} s.\, \mathbf{let}\ f' \leftarrow \mathit{write}\,(s, f)\ \mathbf{in}\ \mathit{close}\, f') : \mathit{File} \to^{\bullet} (\mathit{String} \to^{\circ} ())$$

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It is always safe to use unlimited values just once. We have the subkinding relation $\vdash \mathsf{Type}^{\bullet} \leq \mathsf{Type}^{\circ}$.

Multi-shot handlers abuse linear resources

We get the same problem as Links if we only track value linearity in the presence of multi-shot handlers.

$$
\begin{aligned}
&\mathit{dubiousWrite}_{\text{✗}} \;:\; \mathit{File} \rightarrow^{\bullet} ()\,!\,\{\mathit{Choose} : () \twoheadrightarrow \mathit{Bool}\}\\
&\mathit{dubiousWrite}_{\text{✗}} = \lambda^{\bullet} f.\\
&\quad \textbf{let}\ b \leftarrow (\textbf{do}\ \mathit{Choose}\ ())^{\{\mathit{Choose}:() \twoheadrightarrow \mathit{Bool}\}}\ \textbf{in}\\
&\quad \left.\begin{array}{l}\textbf{let}\ s \leftarrow \textbf{if}\ b\ \textbf{then}\ \text{"}A\text{"}\ \textbf{else}\ \text{"}B\text{"}\ \textbf{in}\\ \textbf{let}\ f' \leftarrow \mathit{write}\,(s, f)\ \textbf{in}\ \mathit{close}\ f'\end{array}\right\}\ \text{continuation of } \mathit{Choose}
\end{aligned}
$$

$$
\begin{aligned}
&\textbf{let}\ f \leftarrow \mathit{open}\,\text{"C.txt"}\ \textbf{in}\\
&\textbf{handle}\ (\mathit{dubiousWrite}_{\text{✗}}\ f)\ \textbf{with}\ \{\mathit{Choose}\ \_\ r \mapsto r\ \mathit{true}\,;r\ \mathit{false}\}
\end{aligned}
$$

Control Flow Linearity in F°_{eff}

Ctrl flow linearity restricts how many times control may enter a local context.

Ctrl flow linearity characterises whether a local context captures linear resources.

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The continuation (context) of *Choose* is control flow linear.

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\textbf{let } s \leftarrow \textbf{if } b \textbf{ then } \text{"}\mathit{A}\text{"} \textbf{ else } \text{"}\mathit{B}\text{"} \textbf{ in} \\
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$$

Control Flow Linearity in $\mathrm{F}^{\circ}_{\mathrm{eff}}$

$\mathrm{F}^{\circ}_{\mathrm{eff}}$ tracks the control flow linearity at the granularity of operations ($\mathit{Choose} : () \twoheadrightarrow^{Y} \mathit{Bool}$), which represents the control flow linearity of their continuations.

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Let-bindings ($\mathbf{let}^{Y}\, x \leftarrow M \;\mathbf{in}\; N$) are annotated with the control flow linearity of the local context (i.e., $\mathbf{let}^{Y}\, x \leftarrow \_ \;\mathbf{in}\; N$).

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$$
\begin{aligned}
&\mathit{dubiousWrite}_{\checkmark} \ :\ \mathit{File} \to^{\bullet} ()\,!\,\{\mathit{Choose} : () \twoheadrightarrow^{\circ} \mathit{Bool}\} \\
&\mathit{dubiousWrite}_{\checkmark} = \lambda^{\bullet} f. \\
&\qquad \mathbf{let}^{\circ} b \leftarrow (\mathbf{do}\ \mathit{Choose}\ ())^{\{\mathit{Choose}:() \twoheadrightarrow^{\circ} \mathit{Bool}\}}\ \mathbf{in} \\
&\qquad \left.\begin{aligned} &\mathbf{let}^{\circ} s \leftarrow \mathbf{if}\ b\ \mathbf{then}\ \text{"A"}\ \mathbf{else}\ \text{"B"}\ \mathbf{in} \\ &\mathbf{let}^{\bullet} f' \leftarrow \mathit{write}\,(s, f)\ \mathbf{in}\ \mathit{close}\, f' \end{aligned}\right\}\ \text{continuation of } \mathit{Choose}
\end{aligned}
$$

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&\mathbf{let}\ f \leftarrow \mathit{open}\ \text{"C.txt"}\ \mathbf{in} \\
&\mathbf{handle}\ (\mathit{dubiousWrite}_{\checkmark}\ f)\ \mathbf{with}\ \{\mathit{Choose}\ \_\ r \mapsto r\ \mathit{true}\,; r\ \mathit{false}\}
\end{aligned}
$$

Ill-typed!

Linear effect rows can be used as unlimited ones

$\mathrm{F}^{\circ}_{\text{eff}}$ lifts the control flow linearity of operations to effect rows.

$$
\begin{aligned}
&(\mathit{Choose} : () \twoheadrightarrow^{\circ} \mathit{Bool}) && : \mathrm{Row}^{\circ} \\
&(\mathit{Choose} : () \twoheadrightarrow^{\bullet} \mathit{Bool}) && : \mathrm{Row}^{\bullet} \\
&(L_1 : \circ ; L_2 : \circ ; L_3 : \bullet) && : \mathrm{Row}^{\bullet}
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\end{aligned}$$

It is always safe to use control-flow-linear operations in an unlimited context. We have the subkinding relation $\vdash \mathrm{Row}^{\circ} \leq \mathrm{Row}^{\bullet}$. For instance,

$$\begin{aligned}
&\mathit{tossCoin} \ : \ \forall \mu^{\mathrm{Row}^{\bullet}}.(() \rightarrow^{\bullet} \mathit{Bool} \,!\, \{\mu\}) \rightarrow^{\bullet} \mathit{String} \,!\, \{\mu\} \\
&\mathit{tossCoin} = \Lambda \mu^{\mathrm{Row}^{\bullet}}.\lambda^{\bullet} g.\ \mathbf{let}^{\bullet}\ b \leftarrow g\,()\ \mathbf{in}\ \mathbf{if}\ b\ \mathbf{then}\ \text{"}\mathit{heads}\text{"}\ \mathbf{else}\ \text{"}\mathit{tails}\text{"}
\end{aligned}$$

Control flow linearity is dual to value linearity!

Control Flow Linearity in Links

The original Links does not track control flow linearity.

```
links> fun(ch:End) {do L; close(ch)};
fun : forall (ρ::Row) . (End) {L:() => () | ρ}~> ()
```

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```

We use **xlin** to claim that the current context is control flow linear, and **lindo** to invoke linear operations.

```
links> fun(ch:End) {xlin; lindo L; close(ch)};
fun : forall (ρ::Row(Lin)) . () {L:() =@ () | ρ}~> ()
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links> fun(ch:End) {xlin; lindo L; close(ch)};
fun : forall (ρ::Row(Lin)) . () {L:() =@ () | ρ}~> ()
```

Linear operations can only be handled by linear handlers.

```
links> fun(ch:End) {
  handle ({ xlin; lindo L; close(ch) }) { case <L =@ r> -> xlin; r(()) }
}
fun : forall (θ:Presence(Lin)) (row:Row(Lin)) . (End) {L{θ} | ρ}~> ()
```

xlin is a modality ?

`xlin` creates a linear scope.

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$\square A$: A linear type A

$\square \ell$: A control-flow-linear operation ℓ

$\square (A \,!\, \{\ell_1 \,;\, \ell_2\}) = \square A \,!\, \square \{\ell_1 \,;\, \ell_2\} = \square A \,!\, \{\square \ell_1 \,;\, \square \ell_2\}$

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$$\frac{\Gamma, ✂ \vdash V : A}{\Gamma \vdash \mathrm{box}\; V : \Box A}\;\textsc{T-Box} \qquad \frac{\Gamma \vdash V : \Box A}{\Gamma, ✂, \Gamma' \vdash \mathrm{unbox}\; V : A}\;\textsc{T-Unbox} \qquad \frac{}{\Gamma, x : A, \Gamma' \vdash x : A}\;\textsc{T-Var}$$

$$\frac{\Gamma, ✂ \vdash M : A \,!\, E}{\Gamma \vdash \mathrm{box}\; M : \Box A \,!\, \Box E}\;\textsc{T-BoxC}$$

The handler rule guarantees that $\Box\ell$ is handled by resuming exactly once.

Problems with Subkinding-based Linear Types

Linear types in $\mathsf{F}^{\circ}_{\text{eff}}$ (and LINKS) can be annoying.

$$\mathit{verboseId} \;:\; \forall \mu^{\mathrm{Row}^{Y_1}}\, \alpha^{\mathrm{Type}^{Y_2}}.\, \alpha \longrightarrow^{Y_0} \alpha \,!\, \{\mathit{Print} : \mathit{String} \twoheadrightarrow^{Y_3} ()\,;\mu\}$$
$$\mathit{verboseId} = \Lambda \mu^{\mathrm{Row}^{Y_1}}\, \alpha^{\mathrm{Type}^{Y_2}}.\, \lambda^{Y_0} x.\, \mathbf{let}^{Y_4}\, () \leftarrow \mathbf{do}\ \mathit{Print}\ \text{"}\mathit{idiscalled}\text{"}\ \mathbf{in}\ x$$

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We have ten different types for *verboseId*, none of which is the most general.

$$\begin{array}{ll} \forall \mu^{\bullet}\ \alpha^{\bullet}.\alpha \to^{\bullet} \alpha\,!\,\{\mathit{Print} : \bullet\,;\mu\} & \forall \mu^{\bullet}\ \alpha^{\bullet}.\alpha \to^{\circ} \alpha\,!\,\{\mathit{Print} : \bullet\,;\mu\} \\ \forall \mu^{\bullet}\ \alpha^{\bullet}.\alpha \to^{\bullet} \alpha\,!\,\{\mathit{Print} : \circ\,;\mu\} & \forall \mu^{\bullet}\ \alpha^{\bullet}.\alpha \to^{\circ} \alpha\,!\,\{\mathit{Print} : \circ\,;\mu\} \\ \forall \mu^{\circ}\ \alpha^{\bullet}.\alpha \to^{\bullet} \alpha\,!\,\{\mathit{Print} : \bullet\,;\mu\} & \forall \mu^{\circ}\ \alpha^{\bullet}.\alpha \to^{\circ} \alpha\,!\,\{\mathit{Print} : \bullet\,;\mu\} \\ \forall \mu^{\circ}\ \alpha^{\bullet}.\alpha \to^{\bullet} \alpha\,!\,\{\mathit{Print} : \circ\,;\mu\} & \forall \mu^{\circ}\ \alpha^{\bullet}.\alpha \to^{\circ} \alpha\,!\,\{\mathit{Print} : \circ\,;\mu\} \\ \forall \mu^{\circ}\ \alpha^{\circ}.\alpha \to^{\bullet} \alpha\,!\,\{\mathit{Print} : \circ\,;\mu\} & \forall \mu^{\circ}\ \alpha^{\circ}.\alpha \to^{\circ} \alpha\,!\,\{\mathit{Print} : \circ\,;\mu\} \end{array}$$

We can restore principal types by abstracting over linearity and introducing constraints on linearity.

$$\begin{aligned} \mathit{verboseId} &: \forall \alpha\, \mu\, \phi\, \phi'. (\alpha \leq \phi) \Rightarrow \alpha \to^{\phi'} \alpha\,!\,\{\mathit{Print} : \phi; \mu\} \\ \mathit{verboseId} &= \lambda x.\, \mathbf{do}\ \mathit{Print}\ \text{"42"}\ ;\ x \end{aligned}$$

Problems with Row-based Effect Types

Effect row types of sequenced computations must be unified.

$$
\begin{aligned}
&\mathit{sandwichClose} \;:\; (() \rightarrow^{\bullet} () \,!\, \{R_1\}, \mathit{File}, () \rightarrow^{\bullet} () \,!\, \{R_2\}) \rightarrow^{\bullet} () \,!\, \{R\} \\
&\mathit{sandwichClose} = \lambda^{\bullet}(g, f, h).\ \mathbf{let}^{\circ}\,() \leftarrow g\,()\ \mathbf{in}\ \mathbf{let}^{\bullet}\,() \leftarrow \mathit{close}\, f\ \mathbf{in}\ h\,()
\end{aligned}
$$

We can only have $R_1 = R_2 = R$, which overly restricts that operations invoked in h must be control flow linear.

We support row subtyping again by qualified types.

$$\begin{aligned}
\mathit{sandwichClose} \;&:\; \forall \mu_1\, \mu_2\, \mu.(\mu_1 \leqslant \mu, \mu_2 \leqslant \mu, \mathit{File} \preceq \mu_1) \\
&\quad \Rightarrow (() \to^{\bullet} ()\,!\,\{\mu_1\}, \mathit{File}, () \to^{\bullet} ()\,!\,\{\mu_2\}) \to^{\bullet} ()\,!\,\{\mu\} \\
\mathit{sandwichClose} \;&=\; \lambda^{\bullet}(g, f, h).\ \mathbf{let}\ () \leftarrow g\,()\ \mathbf{in}\ \mathbf{let}\ () \leftarrow \mathit{close}\, f\ \mathbf{in}\ h\,()
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Qualified types is expressive. Q°_{eff} has a full type inference with constraint solving which does not require any type or linearity annotations.

Qualified Effect Types in Q°_{eff}

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Interesting interaction between row constraints and linearity constraints: $\mu_1 \leqslant \mu_2$ and $\circ \preceq \mu_2$ implies $\circ \preceq \mu_1$.

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Interesting interaction between row constraints and linearity constraints: $\mu_1 \leqslant \mu_2$ and $\circ \preceq \mu_2$ implies $\circ \preceq \mu_1$.

But having explicit constraint sets in types is still a pain?

Algebraic Subtyping for Linear Types and Effect Types

Use algebraic subtyping.

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Algebraic subtyping for row types is standard. Informally,

$$\frac{\Gamma \vdash M : A \,!\, R_1 \qquad N : B \,!\, R_2}{\Gamma \vdash M; N : B \,!\, R_1 \sqcup R_2}$$

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Algebraic subtyping for linear types is more interesting. Informally,

$$\begin{aligned} &\lambda x.\lambda y.\lambda z.(x, y, z) &&: \alpha \to \beta \to^{\alpha} \gamma \to^{\alpha \vee \beta} (\alpha, \beta, \gamma) \\ &\lambda x.(x, x) &&: \alpha \wedge \bullet \to (\alpha, \alpha) \end{aligned}$$

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It is easy to extend it with control flow linearity. Informally,

$$\begin{aligned} &\mathit{verboseId} \;:\; \alpha \to \alpha \,!\, \{\mathit{Print} : \phi \vee \alpha \,;\, \mu\} \\ &\mathit{verboseId} = \lambda x.\, \mathbf{do}\ \mathit{Print}\ \text{"}\mathit{idiscalled}\text{"} \,;\, x \end{aligned}$$

Conclusion

- Track control flow linearity when combining linear types with effect handlers.
- Row subtyping is necessary to have a more fine-grained tracking of control flow linearity.

Thank you!