A Theory of Substructural Types and Control

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Abstract
Exceptions are invaluable for structured error handling in high-level languages, but they are at odds with linear types. More generally, control effects may delete or duplicate portions of the stack, which, if we are not careful, can invalidate a function's substructural usage guarantees for values on the stack. We have developed a type-and-effect system that tracks control effects and ensures that values on the stack are never wrongly duplicated or dropped. We present the system first with abstract control effects and prove its soundness. We then give examples of three instantiations with particular control effects, including exceptions and delimited continuations, and show that they meet the soundness criteria for specific control effects.

Categories and Subject Descriptors    D.3.3 [Programming Languages]: Language Constructs and Features
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1. Substructural Types and Control
Consider, for example, a language like Scala (Odersky and Zenger 2005) with mutable references and arithmetic. Here is a method that takes two integers and divides each by the other, returning a pair of references to their quotients:

\[
\text{def } \text{divRef}(z_1: \text{Int}, z_2: \text{Int}) =
\text{new Ref}(z_1 / z_2, \text{new Ref}(z_2 / z_1))
\]

Suppose that references in this language are linear, meaning that they cannot be duplicated, and must be explicitly deallocated rather than implicitly dropped. In such a language, \text{divRef} has a memory leak. Most uses of \text{divRef} are harmless, but consider the expression \text{divRef}(0, 5). The method will raise a division-by-zero exception, but (assuming one reasonable evaluation order) only after it has allocated a reference to hold the result of the first division. Because the method raises an exception but does not return the successfully allocated reference, there is no way for recovery code that catches the exception to free the reference.

In short, exceptions and linear types refuse to get along, because linear types make promises that exceptions do not let them keep.

With affine rather than linear types, however, \text{divRef} is not a problem, because such a type system does not require that references be freed explicitly. In a language with affine types, implicitly dropping a value is just fine—presumably there is a garbage collector—and only duplication is forbidden. Consider, however, adding delimited continuation operators such as shift and reset to a language with affine types. Assuming a method \text{unref} that dereferences and deallocates a reference, we might attempt to define a method \text{squareRef} that takes a reference to an integer, frees it, and returns its contents, squared:

\[
\text{def } \text{twiceTo}(x: \text{Int}) =
\text{shift } \{ (k: \text{Int }\Rightarrow \text{Int}) \Rightarrow k(k(x)) \}
\text{def } \text{squareRef}(r: \text{Ref[Int]}) =
\text{reset } \{ \text{twiceTo}(1) \times r.\text{unref}() \}
\]

Method \text{twiceTo} uses shift to capture its continuation up to the nearest enclosing reset, and it then applies the captured continuation \(k\) twice to the parameter \(x\). Method \text{squareRef} provides the context for \text{twiceTo} to capture, which is to free \(r\) and multiply by its contents:

\[
[ ] \times r.\text{unref}() .
\]

Since \text{twiceTo} uses its continuation twice, the second use of the continuation will access a dangling pointer that the first use freed.

Typically, an affine type system works by imposing two syntactic requirements: a variable of affine type, such as \(r\), cannot appear twice in its scope (up to branching), and a function that closes over an affine variable must itself have an affine type. The \text{squareRef} example violates neither dictum. In the presence of delimited continuations, we need to add a third rule: that a captured continuation that contains an affine value must not duplicated. A simple approximation of this rule is to give all captured continuations an affine (or in a linear system, linear) type. Such a rule would permit some limited uses of delimited continuations, such as...
coroutines, but we will show that this simple rule is overly restrictive.

**Our solution.** The memory leak and dangling pointer in the above examples can be fixed by small changes to the code. For `divRef`, it suffices to ensure that both divisions happen before both allocations:

```plaintext
def divRef(z1: Int, z2: Int) = {
val z12 = z1 / z2
val z21 = z2 / z1
(new Ref(z12), new Ref(z21))
}
```

For `squareRef`, we need the dereferencing to happen once, outside the reset delimiter:

```plaintext
def squareRef(r: Ref[Int]) = {
val z = r.unref()
reset { twiceTo(1) × z }
}
```

Unfortunately, the conservative approximation suggested above, that all continuations be treated linearly, would still disallow these repaired examples. We have designed a type-and-effect system (Lucassen and Gifford 1988) that permits these two repaired versions of the methods while forbidding the original, erroneous versions. The key idea is to assign to each expression a control effect that reflects whether it may duplicate or drop its continuation, and to prohibit using an expression in a context that cannot be treated as the control effect allows. In this paper, we

- exhibit a **generic** type system for substructural types and control defined in terms of an unspecified, abstract control effect (§4);
- give soundness criteria for the abstract control effect and prove type safety for the generic system, relying on the soundness of the abstract control effect (§5); and
- demonstrate three concrete instantiations of control effects and prove that they meet the soundness criteria (§6).

The generic type-and-effect system in §4 is defined as an extension to $\lambda_{URAL}$ (Ahmed et al. 2005), a substructural $\lambda$ calculus, which we review in §3, after discussing related work in §2.

2. **Related Work and Comparison**

This work is not the first to relate substructural types to control operators and control effects. Thielecke (2003) shows how to use a type-and-effect system to reason about how expressions treat their continuations. In particular, he gives a continuation-passing style transform where continuations that will be used linearly are given a linear type. Thielecke notes that many useful applications of continuations treat them linearly. However, his goals are different than ours. He uses substructural types in his object language to reason about how continuations will be used in a non-substructural source language, whereas we want to reason about continuations in order to safely use substructural types. Thielecke has linear types only in the object language of his translation, whereas we are interested in linear (and other substructural) types in the source language.

Other recent work relates substructural logics and control. Kiselyov and Shan (2007) use a substructural logic to allow the “dynamic” control operator `shift` to modify answer types in a typed setting. Unlike this work, their terms are structures in substructural logic, not their types. Mazurak and Zdancewic’s Lollipop (2010) relates double negation elimination in classical linear logic to delimited control.

We draw significantly on other work on control operators, effect systems, and substructural types as well.

**Control operators.** The literature contains a large vocabulary of control operators, extending back to ISWIM’s `J` operator (Landin 1965), Reynolds’s `escape` (1972), and Scheme’s `call/cc` (Clinger 1985). However, for integration in a language with substructural types, control operators with delimited extent, originating with Felleisen’s $F$ (1988), are most appropriate, because without some way to mask out control effects, any use of control pollutes the entire program and severely limits the utility of substructural types.

As examples of control features to add to our calculus, we consider the delimited continuation operators `shift` and `reset` (Danvy and Filinski 1989) and structured exception handling (Goodenough 1975). Both `shiftReset` and structured exceptions have been combined with type-and-effect systems to make them more amenable to static reasoning.

**Type-and-effect systems for control.** Java (Gosling et al. 1996) has checked exceptions, an effect system for tracking the exceptions that a method may raise. Our version of exception effects is similar to Java’s, except that we offer effect polymorphism, which makes higher-order programming with checked exceptions more convenient. Our type system for exceptions appears in §6.3.

Because Danvy and Filinski’s `shift` (1989) captures a delimited continuation up to the nearest `reset` delimiter, typing `shift` and `reset` requires some nonlocal means of communicating types between delimiters and control operators. They realize this communication with a type-and-effect system, which allows `shift` to capture and compose continuations of varying types. Asai and Kameyama (2007) extend Danvy and Filinski’s (monomorphic) type system with polymorphism, which includes polymorphism of answer types. We give two substructural type systems with `shift` and `reset`. Section 6.1 presents a simpler version that severely limits the answer types of continuations that may be captured. Then, in §6.2, we combine the simpler system with a polymorphic version of Danvy and Filinski’s, similar to Asai and Kameyama’s, to allow answer-type modification and polymorphism in a substructural setting.
Substructural type systems. Researchers have proposed a plethora of substructural type systems. These range from minimalistic models (Wadler 1992; Bierman 1993; Barber 1996; Morrisett et al. 2005) based on Girard’s linear logic (1987), to real programming languages, which are often oriented toward specific problems such as safety in low-level languages (Grossman et al. 2002), typestate and protocol checking (Aldrich et al. 2009), or security (Swamy et al. 2010).

We translate our substructural type-and-effect system into Ahmed et al.’s λURAL (2005), which is a polymorphic λ calculus that supports a variety of substructural typing disciplines. We provide a primer on λURAL in §3.

Motivation. The software engineering case for structured exception handling is widely acknowledged and understood, but shift and reset (Danvy and Filinski 1989), the other control operators discussed in this paper, are more obscure. The essential idea is simple: whereas raising an exception discards the context up to some delimiter—the exception handler—shift captures and reifies the context up to its delimiter, reset, which allows reinstating the context later. These control operators may be used to implement exceptions, by capturing continuations but never reinvoking them, but they may also express other control structures, such as coroutines and cooperative multithreading, and they may be used to abstract non-determinism and search in an elegant way.

Our goal is to safely integrate control operators with substructural types. A substructural type system regulates the order and number of uses of data by statically ensuring that some values be used at most once, at least once, or exactly once (Walker 2005). Like shift and reset, substructural types are a general facility that can express a variety of specific language features, mostly for the purpose of managing stateful resources, such as typestate, region-based memory management, and session types.

The direct impetus for this work is the design of the programming language Alms (Tov and Pucella 2011), which provides both exceptions and affine types, a variety of substructural type that can prohibit reusing particular values. As demonstrated in §1, the combination of affine types and exceptions is not a problem. However, as we observe in that previous work, “we anticipate that safely combining linearity with exceptions requires a type-and-effect system to track when raising an exception would implicitly discard linear values.” Our desire to add linear types to Alms motivates this development of a general theory of substructural types and control effects.

3. Syntax and Semantics of λURAL

In this paper, we add control effects to Ahmed et al.’s λURAL (2005), a substructural λ calculus. Our presentation of λURAL is heavily based on theirs, with a few small changes.

v ::= x | λx.e | Δ.e | () | inl v | inr v (values)
e ::= v | e_1 e_2 | e_1 | let () = e_1 in e_2 (expressions)
    | case e of inl x_1 → e_1; inr x_2 → e_2
q ∈ {U, R, A, L} (qualifier constants)
ξ ::= α | q (qualifiers)
τ ::= α | τ_1 → τ_2 | ∀α:κ.τ | 1 | τ_1 ⊕ τ_2 (pretypes)
τ ::= α | ξτ (types)
ι ::= ξ | τ (type-level terms)
κ ::= QUAL | τ | * (kinds)

Figure 1. λURAL syntax

The syntax of λURAL appears in Figure 1.1

The expression level. Values include abstractions, type abstractions, the unit value, and injections into a sum. (This differs from Ahmed et al.’s presentation of λURAL by including sums—additive disjunctions, to be precise—rather than multiplicative conjunctions. Our theorems handle both, but we omit products in this paper for brevity. Sums are more useful for our purposes here.) Expressions include values, application, type application, unit elimination, and sum elimination. Following Ahmed et al., we elide the formal parameter in type abstractions and the actual parameter in type applications.

The type level. Expressions in λURAL are classified by types (τ), but the language at the type level is much richer. Four constant qualifiers (q) distinguish four substructural properties that may be enforced for values:

L as in linear, for values that may be neither duplicated nor implicitly dropped;
A as in affine, for values that may be dropped (weakening) but not duplicated;
R as in relevant, for values that may be duplicated (contraction) but not dropped; and
U as in unlimited, for ordinary values that allow both dropping and duplication.

The four constant qualifiers form a lattice, whereby it is always safe to treat a value as if it has a higher qualifier than its own.

Qualifiers (ξ) include both qualifier constants and type variables, allowing for qualifier polymorphism. Preotypes (τ)

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1This is the black-and-white version of this paper, suitable for printing; a version that uses colors to distinguish non-terminals from two different calculi is available online at www.ccs.neu.edu/~tov/pubs/substructural-control.
We use non-terminal which is why universal quantification (a pretype decorated with its qualifier (elimination rules. Pretypes include type variables, function specify the representation of a value, and its introduction and

The kind level. Types in \( \lambda^{URAL} \) are classified by three kinds \((\kappa)\): QUAL for qualifiers, \(\overline{\kappa}\) for pretypes, and \(*\) for types. Type variables may have any of these three kinds, which is why universal quantification \((\forall\alpha:K.\tau)\) specifies the kind of \(\alpha\).
enforces the type/pretype structure, whereby type constructors such as \( \oplus \) form a pretype from types (rule K-SUM), and decorating a pretype with a qualifier forms a type (rule K-TYPE).

In Figure 4, three judgments relate qualifiers to each other, to types, and to type contexts. Qualifier subsumption (\( \Delta \vdash \xi_1 \preceq \xi_2 \)) defines the qualifier order, with top \( \top \) and bottom \( \bot \). The next judgment bounds a type by a qualifier; judgment \( \Delta \vdash \tau \preceq \xi \) means that values of type \( \tau \) may safely be used according to the structural rules implied by \( \xi \). Finally, bounding a type context by a qualifier (\( \Delta \vdash \Gamma \preceq \xi \)) means that every type in context \( \Gamma \) is bounded by qualifier \( \xi \).

Figure 5 gives rules for splitting a type context into two (\( \Delta \vdash \Gamma \rhd \Gamma_1 \oplus \Gamma_2 \)), which is necessary for distributing typing assumptions to multiple subterms of a term. Any variable may be distributed to one side or the other. Rule S-CONTRACT implements the contraction structural rule, whereby variables whose type is unlimited or relevant may be duplicated to both contexts.

Finally, Figure 6 gives the judgment for assigning types to expressions (\( \Delta; \Gamma \vdash e : \tau \)). Several points are worthy of note:

- The weakening rule, T-WEEK, allows discarding portions of the context that are upper-bounded by \( A \), which means that all the values dropped are either affine or unlimited.
- The rules for application and for unit and sum eliminations, T-APP, T-LETUNIT, and T-CASE, split the context to distribute assumptions to subterms. Note, however, that both branches of a case expression share the same context.
- Rule T-ABS selects a qualifier \( \xi \) for a function type based on bounding the context, \( \Gamma \). This means that the qualifier of a function type must upper bound the qualifiers of the types of the function’s free variables. As we will see in §5, this property is key to our soundness theorem.

4. Generic Control Effects

Rather than add a specific control effect, such as exceptions or delimited continuations, to \( \lambda^{\text{URAL}} \), we aim to design a substructural type system with a general notion of control effect. Thus, in this section, we define a new calculus, \( \lambda^{\text{URAL}}(C) \), parameterized by an unspecified control effect.

4.1 The Control Effect Parameter

In this subsection, we give the form of the parameter that stands for a particular control effect. Our definition of \( \lambda^{\text{URAL}}(C) \) relies only on this abstract specification of the formal parameter. In §5, we specify several properties of the parameter that are sufficient for a generic soundness theorem to hold, and in §6 we give three examples of actual control effect parameters.

Definition 4.1 (Control effect).

A control effect instance is a triple \((C, \bot_C, \otimes)\) where \( C \) is a set of control effects \( C \), \( \bot_C \in C \) is a distinguished pure effect that denotes no actual control, and \( \otimes : C \times C \rightarrow C \) is an associative, partial, binary operation denoting effect sequencing.
\[ D \vdash i : k \]  (kinding type-level terms)

\[
\begin{array}{l}
\text{C-K-Bot} \\
D \vdash \bot_c : \text{CTL}
\end{array}
\]

\[
\begin{array}{l}
\text{C-K-ARR} \\
D \vdash t_1 : * & D \vdash t_2 : * & D \vdash c : \text{CTL} \\
D \vdash t_1 \rightleftharpoons t_2 : \overline{c}
\end{array}
\]

\[
\begin{array}{l}
\text{C-K-ALL} \\
D, \alpha : k \vdash t : * & D \vdash c : \text{CTL} \\
D \vdash \forall \alpha : k. t : \overline{c}
\end{array}
\]

\[ D \vdash c \geq \xi \]  (qualifier bound for control effects)

\[
\begin{array}{l}
\text{C-B-PURE} \\
D \vdash \xi : \text{QUAL} & D \vdash \bot_c \geq \xi
\end{array}
\]

\[
\begin{array}{l}
\text{C-B-UNL} \\
D \vdash c : \text{CTL} & D \vdash c \geq U
\end{array}
\]

\[
\begin{array}{l}
D \vdash c_1 \leq c_2
\end{array}
\]

\[ D \vdash c_1 \leq c \]  (control effect subsumption)

\[
\begin{array}{l}
\text{CSUB-REFL} \\
D \vdash c : \text{CTL} & D \vdash c \leq c
\end{array}
\]

\[
\begin{array}{l}
\text{CSUB-TRANS} \\
D \vdash c_1 \leq c' & D \vdash c' \leq c_2
\end{array}
\]

**Figure 7.** \( \lambda^\text{URAL}(\xi) \) statics (i): updated rules

For example, in §6.3 we add exception handling to \( \lambda^\text{URAL}(\xi) \). An exception effect is the set of exceptions that may be raised by an expression, the distinguished pure effect \( \bot_c \) is the empty set, and sequencing is set union. A non-empty effect indicates that an expression may discard part of its continuation, whereas the empty effect guarantees that an expression treats its continuation linearly.

In simple cases, as with exceptions, effects form a join semilattice where sequencing is the join, but this is not necessarily true in general (§6.2).

### 4.2 Updated Syntax

In \( \lambda^\text{URAL}(\xi) \), control effects constitute a fourth kind of type-level term, in addition to qualifiers, pretypes, and types. We add a new kind, CTL, and include abstract control effects (\( c \in \xi \)) among the type-level terms:

\[
k :: \text{QUAL} | \overline{c} | * | \text{CTL} \quad \text{(kinds)}
\]

\[
i :: \xi | \overline{t} | t | c \quad \text{(type-level terms)}
\]

Function and universal pretypes now have latent effects, which record the effect that will happen when an abstraction is applied. We update the definition of pretypes to include these latent effects:

\[
\overline{t} :: \cdots | t_1 \overset{c}{\rightleftharpoons} t_2 | \forall \alpha : k. t \quad \text{(pretypes)}
\]

\[
t :: \alpha | \xi \overline{t} \quad \text{(types)}
\]

The other pretype (\( \overline{t} \)) productions remain unchanged.

For non-terminal symbols that differ between \( \lambda^\text{URAL} \) and \( \lambda^\text{URAL}(\xi) \), we use Roman letters (\( t, k, G, \ldots \)) for \( \lambda^\text{URAL}(\xi) \) to distinguish them from \( \lambda^\text{URAL} \), where they appeared in Greek (\( \tau, \kappa, \Gamma, \ldots \)).

### 4.3 Static Semantics of \( \lambda^\text{URAL}(\xi) \)

All type system judgments from \( \lambda^\text{URAL} \) are updated for \( \lambda^\text{URAL}(\xi) \), and \( \lambda^\text{URAL}(\xi) \) adds two new judgments as well. The kinding and expression typing judgments are the only two to change significantly. The judgments for bounding types (\( D \vdash t \leq \xi \)), bounding type contexts (\( D \vdash G \leq \xi \)), and splitting type contexts (\( D \vdash G \leadsto G_1 \sqcup G_2 \)) are isomorphic to the \( \lambda^\text{URAL} \) versions of those judgments from Figures 4 and 5. They are merely updated with new non-terminals as appropriate (\( i.e., \kappa \) to \( k, \overline{t} \) to \( \overline{t} \), and \( \tau \) to \( t \)).

**Kinding.** We identify control effects as the type-level terms (\( i \)) that are assigned kind CTL by the kinding judgment. Figure 7 shows one new kinding rule, C-K-BOT, which assigns kind CTL to the pure effect \( \bot_c \). We update rules C-K-ARR and C-K-ALL to account for latent effects in function and universal pretypes. The remaining kinding rules are the same as for \( \lambda^\text{URAL} \), with non-terminals mutatis mutandis. Specific control effect instances (§6) must define additional kinding rules for their particular effects.

**Control effect judgments.** The first new judgment for control effects (\( D \vdash c \geq \xi \), Figure 8) relates control effects to qualifiers. This gives the meaning of a control effect in terms of a lower bound for how an expression with that effect may treat its own continuation. For example, if an expression \( e \) has some effect \( c \) such that \( D \vdash c \geq A \), this indicates that \( e \) may drop but not duplicate its continuation. We give two rules here:

- Rule C-B-PURE says that the pure effect is bounded by any qualifier, which means that a pure expression satisfies any requirement for how it treats its continuation.
- Rule C-B-UNL says that all control effects are bounded by \( U \), which means that we may assume, conservatively, that any expression might freely duplicate or drop its continuation.

Specific instances of the control effect parameter will extend this judgment to take into account the properties of a particular control effect.

The second judgment for control effects (\( D \vdash c_1 \leq c_2 \)) defines a subsumption order for control effects. This means that an expression whose effect is \( c_1 \) may be safely considered to have effect \( c_2 \). Only two rules for the judgment
appear in Figure 8, which together ensure that control effect subsumption is a preorder. As with control effect bounding, specific control effect instances will extend this judgment.

Expression typing. The expression typing judgment for $\lambda^{URAL}(\epsilon)$ (Figure 9) assigns not only a type $t$ but an effect $e$ to expressions: $D; G \vdash e : t; e$. Having seven premises, the rule for applications (C-T-App) is unwieldy, but it likely gives the most insight into how $\lambda^{URAL}(\epsilon)$ works:

1. The first premise, as in $\lambda^{URAL}$, splits the type context $G$ into $G_1$ for typing $e_1$ and $G_2$ for typing $e_2$.
2-3. As in $\lambda^{URAL}$, these premises assign types to expressions $e_1$ and $e_2$, but they assign control effects $c_1$ and $c_2$ as well.
4. This premise relates the type of $e_1$ to the effect of $e_2$ to ensure that $e_2$'s effect does not violate $e_1$'s invariants. Because we fix a left-to-right evaluation order, by the time $e_2$ gets to run, $e_1$ has reduced to a value of type $\xi_1(t_1 \xrightarrow{\alpha} t_2)$, which thus may be treated according to qualifier $\xi_1$. Because that value is part of $e_2$'s continuation, we require that $e_2$'s effect, $c_2$, be lower-bounded by $\xi_1$. In other words, $e_2$ will treat its continuation no more liberally than $\xi_1$ allows.
5-6. These premises relate the free variables of $e_2$ to the effect of $e_1$. Due to the evaluation order, $e_2$ appears unevaluated in $e_1$'s continuation, which means that if $e_1$ drops or duplicates its continuation then $e_2$ may be evaluated never or more than once. Premise (5) says that the type context for typing $e_2$, and thus $e_2$'s free variables, are bounded above by some qualifier $\xi_2$, and this qualifier

We consider the premises in order:

Figure 9. $\lambda^{URAL}(\epsilon)$ statics (iii): typing
thus indicates how many times it is safe to evaluate $e_2$. Premise (6) lower bounds $e_1$’s effect, $c_1$, by $\xi_2$, ensuring that $e_1$’s effect treats $e_2$ properly.

(7) The net effect of the application expression is a sequence of the effect of $e_1$ ($c_1$), then the effect of $e_2$ ($c_2$), and finally the latent effect of the function to which $e_1$ must evaluate ($c$): $c_1 \ominus c_2 \ominus c$. This premise checks that those three effects may be sequenced in that order according to a particular control effect’s definition of sequencing and the kinding judgment.

Rules C-T-LETUNIT and C-T-CASE (unit and sum elimination) are similar, since they need to safely sequence two subexpressions. Both rules follow rule C-T-APP in relating the effect of the first subexpression to the type context of the second and effect of the second to the qualifier of the first. Rule C-T-TAPP (type application), while dealing with only one effectful subexpression, needs to sequence the effect of evaluating the expression in a type application with the latent effect of the resulting type abstraction value.

The subsumption rule C-T-SUBSUME implements control effect subsumption, whereby an expression of effect $c$ may also be considered to have effect $c'$ if $c$ is less than $c'$ in the control effect subsumption order. C-T-WISE, which handles weakening, is unchanged from $\lambda_{URAL}$.

The remaining rules are for typing values, which always have the pure effect $\perp_c$. Rules C-T-UNIT, C-T-INL, and C-T-INR, for unit and sum introduction, are unchanged from $\lambda_{URAL}$, except that each of them assigns the pure effect. Rules C-T-ABS and C-T-TABS also assign the pure effect to their values, but each records the effect of the abstraction body as the latent effect in the resulting type.

### 5. The Generic Theory

To prove type safety for $\lambda_{URAL}(\mathcal{E})$, we define a type-preserving translation to $\lambda_{URAL}$. Rather than provide a reduction semantics for $\lambda_{URAL}(\mathcal{E})$, we define its operational semantics in terms of the translation and the reduction semantics of $\lambda_{URAL}$ (§3.1). Thus, if we can show that all well-typed $\lambda_{URAL}(\mathcal{E})$ programs translate to well-typed $\lambda_{URAL}$ programs, then $\lambda_{URAL}$’s type safety theorem applies to $\lambda_{URAL}(\mathcal{E})$ as well.

The translation is into what Danvy and Filinski (1989) call *continuation-composing style* (henceforth “CCoS”). It is similar to continuation-passing style, but unlike continuation-passing style it still relies on the object language’s order of evaluation.

In order to specify the translation and prove the propositions specified later in this section, we impose several more requirements on the abstract control effect parameter. As the semantics of $\lambda_{URAL}(\mathcal{E})$ was parameterized by an abstract control effect, so is the theory of $\lambda_{URAL}(\mathcal{E})$ parameterized by several definitions and properties that a control effect must satisfy.

The development of this section is constrained by several dependencies, so we provide an outline:

**The Translation Parameter (§5.1).** A control effect instance must supply a few definitions to fully specify its particular CCoS translation.

**The Translation (§5.2).** The definition of the CCoS translation relies on the definitions supplied by the control effect parameter.

**Parameter Properties (§5.3).** A control effect instance must satisfy several properties on which the generic type safety theorem relies.

**Generic Type Safety (§5.4).** The section culminates in a generic proof of type safety for $\lambda_{URAL}(\mathcal{E})$.

### 5.1 The Translation Parameter

**Definition 5.1 (Translation parameter).**

The definition of the generic CCoS translation relies on the following effect-specific definitions:

- a metafunction $(\cdot)^*$ from effects to qualifiers, such that $\perp_c^* = L$ and $\alpha^* = \alpha$;
- a value done$_c$, to use as the initial continuation for a CCoSed program; and
- a pair of answer-type metafunctions $\llangle \cdot \rrangle_-$ and $\llangle \cdot \rrangle_+$, each of which maps a $\lambda_{URAL}$ type and a $\lambda_{URAL}(\mathcal{E})$ effect to a $\lambda_{URAL}$ type.

Intuitively, we can understand metafunctions $(\cdot)^*$, $\llangle \cdot \rrangle_-$, and $\llangle \cdot \rrangle_+$ as relating the effect of a $\lambda_{URAL}$ expression to the type of its translation into $\lambda_{URAL}$. Typically, the CPS translation of an expression of some type $\tau$ yields a type like $(\tau \rightarrow \text{Answer}) \rightarrow \text{Answer}$.

Given a $\lambda_{URAL}(\mathcal{E})$ expression whose translated type is $\tau$ and whose effect is $c$, our translation yields type

$$c^* (\tau \rightarrow \llangle \tau_0, c^+ \rrangle_c) \rightarrow \llangle \tau_0, c^+ \rrangle_c$$

for some answer type $\tau_0$. That is, $(\cdot)^*$ gives the qualifier of the continuation, and the other two metafunctions give the answer types, which may depend on the nature of the control effect. Because they give the answer types in negative and positive positions, respectively, we call $\llangle \tau, c^- \rrangle_c$ the negative answer type and $\llangle \tau, c^+ \rrangle_c$ the positive answer type.

### 5.2 The Translation

In this subsection, we specify the CCoS translation from $\lambda_{URAL}(\mathcal{E})$ to $\lambda_{URAL}$. In several places, we rely on the definitions of $c^*$, done$_c$, $\llangle \tau, c^- \rrangle_c$, and $\llangle \tau, c^+ \rrangle_c$ supplied by the control effect parameter.

The translation for kinds and kind contexts appears in Figure 10. The control effect kind CTL translates to QUAL, and the other three kinds translate to themselves. The translation of a kind context merely translates each kind in its range.
Additional type abstraction added to the front, which matches the addition of the universal quantifier in the type translation, and both translate the body according to the expression translation $\llbracket e \rrbracket_c$. The expression translation is standard except for two unusual aspects of the translation of applications and type applications:

- The result of evaluating $e_1$, bound to $x_1$, is in each case instantiated by a type application, which compensates for the new type abstraction in the translation of abstractions. For the type application case, $x_1$ is instantiated then again, corresponding to the instantiation from the source expression.
- Curiously, the continuation $y$ is $\eta$-expanded to $\lambda x.y x$. While $\eta$-expanding a variable may seem useless, it is actually necessary to obtain a type-preserving translation.

In particular, the reason for this $\eta$ expansion is to handle effect subsumption. Effects in $\lambda^{URAL}(\mathcal{C})$ are translated to qualifiers in $\lambda^{URAL}$, and while $\lambda^{URAL}(\mathcal{C})$ supports effect subsumption directly, there is no analogous qualifier subsumption in $\lambda^{URAL}$. However, qualifier subsumption for function types can be done explicitly using $\eta$ expansion:

**Lemma 5.2** (Dereliction).

If $\Delta; \Gamma \vdash v : \xi(t_1 \rightarrow t_2)$ and $\Delta \vdash \xi \leq \xi'$ then $\Delta; \Gamma \vdash \lambda x. v x : \xi'(t_1 \rightarrow t_2)$.

The proof of Lemma 5.2 relies on another lemma:

**Lemma 5.3** (Value strengthening).

Any qualifier that upper bounds the type of a value also bounds the portion of the type context necessary for typing that value. That is, if $\Delta; \Gamma \vdash v : \tau$ and $\Delta \vdash \tau \leq \xi$ then there exist some $\Gamma_1$ and $\Gamma_2$ such that

- $\Delta \vdash \Gamma \rightarrow \Gamma_1 \oplus \Gamma_2$,
- $\Delta; \Gamma_1 \vdash v : \tau$,
- $\Delta; \Gamma_1 \vdash \Gamma_2 \leq \xi$, and
- $\Delta \vdash \Gamma_2 \leq \Lambda$.

**Proof.** By induction on the typing derivation for $v$. \qed

**Proof of Lemma 5.2.** Choose type contexts $\Gamma_1$ and $\Gamma_2$ according to Lemma 5.3. Then $\Delta; \Gamma_1, x : t_1 \vdash v x : t_2$ by rule T-App. By induction on the length of $\Gamma_1$ and transitivity of qualifier subsumption, we know that $\Delta \vdash \Gamma_1 \leq \xi'$. Then by rule T-Abs, $\Delta; \Gamma_1 \vdash \lambda x. v x : \xi'(t_1 \rightarrow t_2)$, and we change $\Gamma_1$ to $\Gamma$ by rule T-Weak. \qed

**Operational semantics of $\lambda^{URAL}(\mathcal{C})$.** Having defined the translation, we run a program $e$ by applying the CCoS translation and passing it the initial continuation done$_e$. We define the operational semantics of $\lambda^{URAL}(\mathcal{C})$ as a partial fun-
5.3 Parameter Properties

Having defined the CCoS translation, we are now ready to state the additional properties that the abstract control effect parameter must satisfy for the generic type safety theorem (§5.4) to hold:

Parameter Property 1 (Answer types).
1. For all \( \tau \), \( \langle \tau, \bot_c \rangle_c = \langle \tau, \bot_c \rangle_c^+ \).

Rationale. For pure expressions, the negative and positive answer types agree, because a pure expression finishes by calling its continuation. Henceforth, we are justified defining the pure answer type \( \langle \tau \rangle_c = \langle \tau, \bot_c \rangle_c^+ \).

2. If \( D \vdash \tau : \star \) and \( D \vdash c : \text{CTL} \) then \( D^* \vdash \langle \tau, c \rangle_c^+ : \star \) and \( D^* \vdash \langle \tau, c \rangle_c^+ : \star \).

Rationale. For the translation to be well typed, well-kindred types and effects must become well-kindred answer types.

3. For all \( D \), \( \tau \), \( c_1 \neq \bot_c \), and \( c_2 \neq \bot_c \) such that \( D \vdash c_1 \otimes c_2 : \text{CTL} \),

   (a) \( \langle \tau, c_1 \otimes c_2 \rangle_c = \langle \tau, c_2 \rangle_c^+ \),
   (b) \( \langle \tau, c_1 \otimes c_2 \rangle_c = \langle \tau, c_1 \rangle_c^+ \), and
   (c) \( \langle \tau, c_1 \rangle_c = \langle \tau, c_2 \rangle_c^+ \).

Rationale. Effect sequencing must maintain answer types in order for the continuations of sequenced expressions to compose.

4. If \( D \vdash c_1 \preceq c_2 \), then for every type \( \tau \) there exists some type \( \tau' \) such that \( \langle \tau', c_1 \rangle_c = \langle \tau, c_2 \rangle_c^+ \) and \( \langle \tau', c_1 \rangle_c^+ = \langle \tau, c_2 \rangle_c^+ \).

Rationale. For control effect subsumption to be valid, related control effects must generate related answer types.

Parameter Property 2 (Done).
If \( \Delta \vdash \tau \preceq \Delta' \vdash \text{done}_e : (\tau \rightarrow \text{done}_e) \).

Rationale. The done\(_e\) value must be well typed for the translation of a whole program to be well typed.

Parameter Property 3 (Effect sequencing).
If \( D \vdash c_1 \otimes c_2 : \text{CTL} \) then \( D^* \vdash (c_1 \otimes c_2)^+ \preceq c_1^+ \) and \( D^* \vdash (c_1 \otimes c_2)^+ \preceq c_2^+ \).

Rationale. Sequencing lowers the translation of control effects in the qualifier order. This makes sense, because if either of two sequenced expressions may duplicate or discard its continuations, then the compound expression may do the same.

Parameter Property 4 (Bottom and lifting).
1. \( c_1 \otimes c_2 = \bot_c \) if and only if \( c_1 = c_2 = \bot_c \).

Rationale. Sequencing impure expressions should not result in a pure expression.

2. If \( D \vdash \tau, c_1 \otimes c_2 : \text{CTL} \) and \( c_1 \otimes c_2 \neq \bot_c \), then there exist some \( c_1' \neq \bot_c \) and \( c_2' \neq \bot_c \) such that

   - \( D \vdash c_1' \preceq c_1 \),
   - \( D \vdash c_2' \preceq c_2 \),
   - \( c_1' \otimes c_2' = c_1 \otimes c_2 \), and
   - \( D \vdash c_1' \otimes c_2' : \text{CTL} \).

Rationale. This assumption is likely not necessary, but it significantly simplifies the proof by allowing the effects in a sequence to be considered either all pure or all impure.

The final property concerns four lemmas that we state and prove for the generic system in the next subsection. An actual control effect instance needs to extend these lemmas to cover any additional rules added to the relevant judgments:

Parameter Property 5 (New rules).
1. Lemma 5.4 (§5.4) must be extended, by induction on derivations, for any rules added to the kinding judgment \( D \vdash t : k \).

2. Lemma 5.5 (§5.4) must be extended, by induction on derivations, for any rules added to the control effect bounding judgment \( D \vdash c \preceq \xi \).

3. Lemma 5.6 (§5.4) must be extended, by induction on derivations, for any rules added to the control effect subsumption judgment \( D \vdash c_1 \preceq c_2 \).

4. Lemma 5.7 (§5.4) must be extended, by induction on derivations, for any rules added to the expression typing judgment \( D ; G \vdash e : t ; c \).
In §6, we give several example control effects and show that they satisfy the above properties.

### 5.4 Generic Type Safety

Assuming that the above properties hold of the control effect parameter, we can now prove a type safety theorem for $\lambda^{\text{URAL}}(e)$ that leaves the control effect abstract. We sketch the proof here, but the full proof is available online at www.ccs.neu.edu/~tov/pubs/substructural-control.

We begin with a lemma that ensures that control effects translate to well-formed qualifiers:

**Lemma 5.4 (Translation of kindling).**

For all $D$, $i$, and $k$, if $D \vdash i : k$ then $D^* \vdash i^* : k^*$.

We continue with two lemmas concerning how the translation of control effects to qualifiers relates to qualifier subsumption. The former ensures that the control effect bound used by typing rules such as C-T-APP matches the qualifier assigned to the type of a continuation by the CCoS translation. The latter ensures that a larger control effect, which indicates more liberal treatment of a continuation, maps to a smaller qualifier, which indicates more liberal treatment of any value.

**Lemma 5.5 (Translation of effect bounds).**

If $D \vdash c \geq \xi$ then $D^* \vdash c^* \geq c^*$.

**Lemma 5.6 (Translation of effect subsumption).**

If $D \vdash c_1 \leq c_2$ then $D^* \vdash c_2^* \leq c_1^*$.

**Proofs of Lemmas 5.4, 5.5, and 5.6.** By induction on derivations.

The most difficult lemma, and the heart of the proof, is about typing translated expressions. Given a $\lambda^{\text{URAL}}(e)$ expression whose control effect is $c$, the translation of the control effect, $c^*$, is the qualifier of the continuation of the translated expression:

**Lemma 5.7 (Translation of term typing).**

If $D; G \vdash e : t \cdot c$ then

$$D^*; G^* \vdash [e]_{c^*} : \lambda^{\text{CTL}}(t \rightarrow \langle \xi_0, c^* \rangle) \rightarrow \langle \xi_0, c^* \rangle^+.$$  

**Proof.** By induction on the typing derivation, generalizing the induction hypothesis thus:

If $D; G \vdash e : t \cdot c$, then for all $\tau_0$ such that $D^* \vdash \tau_0 : \tau$, and for all $\xi_0$ such that $D^* \vdash \xi_0 \preceq c^*$, we have $D^*; G^* \vdash [e]_{c^*} : \lambda^{\text{CTL}}(t \rightarrow \langle \tau_0, c^* \rangle) \rightarrow \langle \tau_0, c^* \rangle^+$.

We consider two cases here:

**Case**

If $D; G \vdash e : t \cdot c$.

By Property 5 (part 3), $D^* \vdash c^* \preceq c^*$, and thus by Property 1 (part 4), there exists some type $\tau_0'$ such that $\langle \tau_0', c^* \rangle \preceq \langle \tau_0', c^* \rangle$ and $\langle \tau_0', c^* \rangle^+ \preceq \langle \tau_0, c^* \rangle^+$. By the lemma assumption, $D^* \vdash \xi_0 \preceq \xi^*$, and by transitivity of qualifier subsumption, $D^* \vdash \xi_0 \preceq \xi^*$. Thus, we can apply the induction hypothesis at $D; G \vdash e : t \cdot c'$, using the same $\xi_0$ but with $\tau_0'$ for $\tau_0$, yielding

$$D^*; G^* \vdash [e]_{c'} : \lambda^{\text{CTL}}(t \rightarrow \langle \tau_0', c' \rangle) \rightarrow \langle \tau_0', c' \rangle^+.$$  

Then it suffices to substitute $\langle \tau_0', c' \rangle$ for $\langle \tau_0, c \rangle$ and $\langle \tau_0, c \rangle^+$ for $\langle \tau_0', c' \rangle^+$, which we know to be equal by Property 1 (part 4).

$$D; G \vdash e : t \cdot c$$

For rule C-T-APP, we want to show that $\llbracket e \cdot e \rrbracket_{c^*}$ has type

$$\lambda y. [e]_{c^*} (\lambda x. [e]_{c^*}(\lambda x. y))$$

The type derivation is too large to show here in detail, but it hinges on giving the right qualifiers to the types of continuations. We will consider the continuation passed to the whole expression and the continuations constructed for $e_1$, $e_2$, and the function application itself, in turn.

First we consider $y$, the continuation of the whole application expression. Given the type that we need to derive for the whole expression, the qualifier of $y$’s type must be $\xi_0$. Furthermore, from the assumptions of the lemma, we know that $D^* \vdash \xi_0 \preceq \langle c_1 \circ c_2 \circ c \rangle^*$. By Property 3, each of $c_1^*$, $c_2^*$, and $c^*$ is greater than $\langle c_1 \circ c_2 \circ c \rangle^*$, so by transitivity, $\xi_0$ is less than each of these.

Expression $e_1$ has effect $c_1$, so by the induction hypothesis, its continuation may have qualifier $c_1^*$. The continuation passed to $\llbracket e_1 \rrbracket_{c_1^*}$ is

$$\lambda y. [e_2]_{c_1^*} (\lambda x. [e_2]_{c_1^*}(\lambda x. y))$$

whose free variables are $\{y\} \cup \text{fv}(e_2)$. Thus, the qualifier of this function must upper bound both $\xi_0$ and the qualifiers of the types in $G_2$ (the type context for $e_2$). We have $D^* \vdash \xi_0 \preceq c_1^*$ from the previous paragraph. Furthermore, looking at the premises of rule T-APP, we see that $\xi_2$ upper bounds the types in $G_2$ and is less than $c_1^*$ (by Property 5 (part 2)), so by transitivity, $D^* \vdash \xi_2^* \preceq c_1^*$, as desired.

Expression $e_2$ has effect $c_2$, so similarly, its continuation should have qualifier $c_2^*$. The free variables of $e_2$’s continuation are only $y$ and $x_1$, which is the value of $e_1$. We handle $y$ as before. The type of $x_1$ is $\xi_2 (t_1 \rightarrow t_2)$, so it remains to show that $D^* \vdash \xi_1 \preceq c_2^*$, by Property 5 (part 2) applied to the premise $D \vdash c_2 \geq \xi_1$. 


Finally, given that \( x_1 \) has type \( \xi_1 ((t_1 \overset{\xi}{\to} t_2)^*) \), it expects
a continuation whose qualifier is \( \epsilon^* \). The type of \( y \) has
Qualifier \( \xi_0 \), which is less than \( \epsilon^* \). Then by Lemma 5.2
(Dereliction), the type of the \( \eta \) expansion \( \lambda x. y x \) may be
given qualifier \( \epsilon^* \).

**Corollary 5.8** (Translation of program typing).

If \( D; G \models e : t ; \bot \epsilon \) where \( D ; \epsilon \models t \preceq A \), then

\[
D^*; G \vdash \llbracket e \rrbracket_e \text{ done}_c : \llbracket t^* \rrbracket_e .
\]

**Proof.** By Lemma 5.4, Lemma 5.7, Property 2, and rules
QSUB-REFL and T-APP.  

**Lemma 5.9** (\( \lambda \text{URAL} \) safety).

If \( \mathbf{e} : \mathbf{t} \models e : \tau \) and \( e_1 \overset{\epsilon}{\longrightarrow} e_2 \), then either \( \exists v_2 . \epsilon e_2 \equiv v_2 \) or
\( \exists v_3 . e_2 \overset{\epsilon}{\longrightarrow} e_3 \).

**Proof.** See the proof in Ahmed et al. (2005).

**Theorem 5.10** (\( \lambda \text{URAL} \) (\( \xi \)) safety).

If \( \mathbf{e} : \mathbf{t} \models e : \tau \) and \( \mathbf{e} : \mathbf{t} \preceq A \) then \( \epsilon \text{ eval}(e) \neq \text{WRONG} \).

**Proof.** By Corollary 5.8. \( \mathbf{e} : \mathbf{t} \models e : \tau \),
then by Lemma 5.9, either \( \llbracket e \rrbracket_e \text{ done}_c \) reduces to a value
\( v \), in which case \( \epsilon \text{ eval}(e) = v \), or \( \llbracket e \rrbracket_e \text{ done}_c \) diverges, in which case
\( \epsilon \text{ eval}(e) \) is undefined.

## 6. Example Control Effects

In the previous section, we proved type safety for \( \lambda \text{URAL} \xi \),
a substructural \( \lambda \) calculus parameterized by abstract control
effects. In this section, we give three instances of control
effects as described by Definition 4.1 and show that they satisfy
the properties on which the generic type safety theorem depends.

### 6.1 Shift and Reset

We define here a control effect instance for delimited continuations.
In this example, we restrict answer types to the unit type \( \top \) in
order to keep the effects simple. In §6.2, we show how to define a
more general control effect instance that allows answer-type modification.

We add shift and reset to \( \lambda \text{URAL} \xi \) as follows. First, we extend the syntax:

\[
e := \cdots | \text{shift } x \in e | \text{reset } e \quad \text{(expressions)}
\]

We give the dynamics of the new expressions by defining their
CCoS translations, which are standard:

\[
\llbracket \text{reset } e \rrbracket_d = \lambda y . y (\llbracket e \rrbracket_d (\lambda x . x))
\]

\[
\llbracket \text{shift } x \in e \rrbracket_d = \lambda y . (\lambda x . \llbracket e \rrbracket_d (\lambda x' . x'))
\]

\[
(\Lambda . \lambda x . \lambda y . y (y x))
\]

To type shift and reset, we define delimited continuation
effects \( d \) as the dual lattice of the qualifier lattice \( \xi \) with a
new point \( \bot_d \):

\[
d ::= \bot_d \quad \text{(no effect)}
\]

\[
| \alpha \quad \text{(an effect variable)}
\]

\[
| \xi \quad \text{(treats continuation like } \xi) \]

\[
| d_1 \bot d_2 \quad \text{(effect join)}
\]

Let \( D \) be the set of delimited continuation effects \( d \) quotiented
by the following equivalences:

\[
\bigcup \xi = \xi \cup \xi = \xi ;
\]

\[
d \cup \bot_D = \bot_d = d \cup d = d .
\]

(The quotient simplifies defining other functions and relations on delimited continuation effects.) Then we define delimited continuation effects as the triple \((D, \bot, \cup)\).

We extend the type system of \( \lambda \text{URAL} \xi \) with the new
rules in Figure 13. The new kinding rules say that qualiﬁers-as-effects \( \xi \) and joins \((d_1 \cup d_2)\) are well-kinded if their components are.
The new control effect bound rules say that a control effect \( \xi \) is bounded by all qualiﬁers \( \xi \) that are less than \( \xi \) and that any bound of both effects in a join bounds
the join as well. The rules added for effect subsumption efectively axiomatize the delimited continuation effect lattice.
Finally, we add two rules for typing shift and reset. To type an expression \( \epsilon \), subexpression \( e \) may have any effect whatsoever, but must return type \( \top \). (We lift this restriction in §6.2.) Then \( \epsilon \) is pure and also has type \( \top \). To
type \( \text{shift } x \in e \), we give \( x \) type \( \xi (t \overset{\xi}{\to} \top) \) for checking \( e \),
where \( \xi \) is joined with the effect of \( e \) to get the effect of the
whole shift expression. That is, because shift captures its
continuation and gives the reified continuation qualifier \( \xi \), its
effect must be at least \( \xi \), since that qualifier determines how
it might treat its captured continuation.

**Type safety.** To prove type safety for \( \lambda \text{URAL} \xi \) extended
with delimited continuation effects, we need to give the translation parameter as described by Definition 5.1. We define the translation parameter as follows:

\[
\llbracket \tau, d \rrbracket^+_D = \llbracket \tau \rrbracket^+_D = \top_1
\]

\[
\text{done}_D = \lambda x . \langle \rangle
\]

\[
d^* = \begin{cases}
L & \text{if } d = \bot_D \\
\alpha & \text{if } d = \alpha \\
\xi & \text{if } d = \xi \\
U & \text{otherwise}
\end{cases}
\]

Then, we must show that this definition satisfies the properties of §5.3:

**Theorem 6.1** (Delimited continuation properties).

Delimited continuation effects \((D, \bot, \cup)\) satisfy Properties 1–5.

**Proof.**

**Property 1 (Answer types).** We must show several equalities
on answer types, such as \( \llbracket \tau, d_1 \rrbracket^+_D = \llbracket \tau, d_2 \rrbracket^+_D \)},
hold whenever \( d_1 \cup d_2 \) is well formed. All of the equalities are trivial because \( \langle \tau, d \rangle \uplus = \langle \tau, d \rangle \uplus = U1 \).

**Property 2 (Done).** We need to show that \( \Delta_1 \vdash \text{done}_1 : (\tau \rightarrow \langle \tau \rangle) \). Given the definition of \( \text{done}_1 \), we can show \( \Delta_1 \vdash \lambda x. f : (\tau \rightarrow \langle \tau \rangle) \) by a straightforward type derivation.

**Property 3 (Effect sequencing).** We need to show that \( D, d_1 \cup d_2 : \text{CTL} \) implies that \( D^* \vdash (d_1 \cup d_2)^* \leq d_1^* \) and \( D^* \vdash (d_1 \cup d_2)^* \leq d_2^* \). By symmetry, it suffices to show the former:

1. \( D, d_1 \leq d_1 \) by CSUB-REFL
2. \( D, \bot \leq d_2 \) by DSUB-BOT
3. \( D, d_1 \cup \bot \leq d_1 \cup d_2 \) by (1–2), DSUB-JOIN
4. \( D, d_1 \leq d_1 \cup d_2 \) by (3), \( d_1 \cup \bot = d_1 \)
5. \( D^* \vdash (d_1 \cup d_2)^* \leq d_1^* \) by (4), Lemma 5.6.

**Property 4 (Bottom and lifting).**

1. To show that \( d_1 \cup d_2 = \bot \), if and only if \( d_1 = d_2 = \bot \), we consider the quotienting of \( D \).
2. We must also show that if \( D, d_1 \cup d_2 : \text{CTL} \) and \( d_1 \cup d_2 \neq \bot \), then there exist some \( d'_1 \neq \bot \) and \( d'_2 \neq \bot \), with particular properties. For each \( d_i (i \in \{1, 2\}) \), if \( d_i = \bot \), then let \( d'_i = \top \); otherwise, let \( d'_i = d_i \). This ensures that 1–2) each \( D, d_i \leq d'_i \), 3) \( d_1 \cup d_2 = d'_1 \cup d'_2 \), and 4) \( d'_1 \cup d'_2 \) is well formed.

**Property 5 (New rules).**

1. We show that \( D, d \geq \xi \) implies that \( D^* \vdash \xi \leq d^* \), by induction on the derivation. The only new cases to consider are for rules D-B-QUAL and D-B-JOIN.

These require a lemma about the translation of qualifier subsumption derivations.

2. We show that \( D, d_1 \leq d_2 \) implies that \( D^* \vdash d_2^* \geq d_1^* \), again by induction on the derivation. The only nontrivial case is when

\[
D, d_1 \leq d_2 \quad \text{and} \quad D, d_2 \leq d_2^*.
\]

We show that \( D^* \vdash (d_1 \cup d_2)^* \leq (d_1 \cup d_2)^* \) by exhaustively enumerating the possibilities for \( d_1, d_2, d_1', \) and \( d_2' \) such that the premises hold.

3. For translation of typing, we show that \( D, d : \text{CTL} \) implies that \( D^* \vdash d^* : \text{QUAL} \). We proceed, as usual, by a simple induction on the derivation, considering the two new binding rules for delimited continuation effects.

4. For translation of typing, we use the generalized induction hypothesis as in the proof of Lemma 5.7. There are two cases, for shift and reset, each of which requires a large type derivation.

**6.2 Shift and Reset with Answer-Type Modification**

The type-and-effect system for shift and reset described in §6.1 requires that all answer types—the type of all reset expressions—be \( U1 \). Our second example adds answer-type modification (à la Danvy and Filinski 1989), which allows shift to capture and compose continuations of differing types and allows the answer delivered by reset to have any type. Both the syntax and CCCS translation are as in §6.1, but
we change the definition of control effects as follows. An answer-type control effect \( a \) is either the pure effect \( \perp_A \) or a collection of qualifiers \( \xi_1, \ldots, \xi_j \) along with old and new answer types \( t_1 \) and \( t_2 \):

\[
a ::= \perp_A \quad \text{(pure)}
\]

\[
| \quad \Xi(t_1 \rightarrow t_2) \quad \text{(a control effect)}
\]

where \( \Xi ::= \xi_1, \ldots, \xi_j \)

A type derivation \( D; G \vdash \xi : t; \xi_1, \ldots, \xi_j \) may be understood as follows:

- The collection of qualifiers \( \xi_1, \ldots, \xi_j \) keeps track of all the ways that expression \( e \) may treat its context; expression \( e \) may be considered to treat its context according to any qualifier \( \xi \) that lower bounds all of \( \xi_1, \ldots, \xi_j \). We need a collection of qualifiers because qualifiers do not, in the presence of qualifier variables, have greatest lower bounds.

- Evaluated in a context expecting type \( t \) whose original answer type was \( t_1 \), expression \( e \) changes the answer type to \( t_2 \). This means that our type-and-effect judgment, disregarding substructural considerations, is equivalent to the type judgment that Danvy and Filinski write as \( \Gamma, t_1 \vdash e : t, t_2 \).

For answer-type modification effects, we define the partial sequencing operation as follows:

\[
\perp_A \circ a = a
\]

\[
a \circ \perp_A = a
\]

\[
\Xi(t' \rightarrow t_2) \circ \Xi'(t_1 \rightarrow t') = \Xi \Xi'(t_1 \rightarrow t_2).
\]

Any other cases are undefined. Then we define answer-type modification effects as the triple \( (A, \perp_A, \circ) \).

The new type rules for answer-type effects appear in Figure 14. For the most part, these rules treat the collection of qualifiers \( \xi_1, \ldots, \xi_j \) similarly to the delimited continuation effect \( \xi_1 \uplus \cdots \uplus \xi_j \) from §6.1. However, there is some subtlety to the definition of answer-type effect subsumption: the only non-bottom effects related by subsumption are those whose before and after answer types match, pairwise, but the pure effect \( \perp_A \) is less than any effect whose before and after answer types match.

The rules for typing shift and reset expressions are a hybrid of the rules from §6.1, which they follow for the qualifier portion, and the rules from Danvy and Filinski (1989), which they follow for maintaining answer types.
**Type safety.** To prove type safety for \(\lambda_{\text{URAL}}(\mathcal{E})\) extended with answer-type modification, we define the translation parameter as follows:

\[
\begin{align*}
\langle \tau, \bot \rangle_\lambda &= \tau \\
\langle \tau, (t_1 \rightsquigarrow t_2) \rangle_\lambda^- &= t_1^* \\
\langle \tau, (t_1 \rightsquigarrow t_2) \rangle_\lambda^+ &= t_2^* \\
\text{done}_\lambda &= \lambda x. x
\end{align*}
\]

Let \(A\) be the set of exception effect sets (\(\Psi\)). Then we define exception effects as the triple \((X, \emptyset, \cup)\). We consider exception effects as true sets, not merely as the free algebra generated by the syntax. Thus, the subsumption order is set containment:

\[
D \vdash \Psi_1 \subseteq \Psi_2
\] (exception effect subsumption)

The other new type rules for exception effects appear in Figure 15. Note that rule X-B-RAISE says that all exception effects are bounded below by \(A\); this is because exceptions allow an expression to discard its context but not duplicate it. (Of course, the empty exception set \(\emptyset\) is bounded by \(L\) by rule C-B-PURE.)

To define the \(\text{CCoS}\) translation, we assume a run-time representation of exceptions and exception sets as follows:

- There is an exception pretype \(\text{exn}\) such that \(\Delta \vdash \text{exn} : \tau\).
- Each exception \(\psi\) is represented by a \(\lambda_{\text{URAL}}\) value \(\psi^*\), such that \(\Delta; \bullet \vdash \psi^* : \text{exn}\).
- For each exception \(\psi\) and pair of \(\lambda_{\text{URAL}}\) values \(v_1\) and \(v_2\), there is a \(\lambda_{\text{URAL}}\) value \([v_1, v_2]_\psi\) such that

\[
[v_1, v_2]_\psi \psi^* \mathrel{\rightarrow} v_1 \psi^* \quad [v_1, v_2]_\psi \psi'^* \mathrel{\rightarrow} v_2 \psi'^*.
\]

Intuitively, \([v_1, v_2]_\psi\) performs case analysis on exception values: when applied to exception \(\psi\), it passes the exception to \(v_1\), and when applied to any other exception, it passes the exception to \(v_2\).

For exception effects, we use a typed CCoS translation that takes an extra parameter: the exception effect of the expression to be translated. We assume that the generic CCoS has been updated to translate type derivations as well in order...
to propagate control effects correctly. Then we can give the CCoS translation for exceptions:

\[ \llbracket \text{raise } \psi \rrbracket_{\Psi}^{\tau} = \lambda \_ . \text{inl } \psi^* \]

\[ \llbracket e_1 \text{ handle } \psi \rightarrow e_2 \rrbracket_{\Psi}^{\tau} = \lambda y . (v, y) (\llbracket e_1 \rrbracket_{\Psi}^x \cup \llbracket e_2 \rrbracket_{\Psi}^y) (\lambda x . \text{inr } x) \]

where \( v = \begin{cases} \lambda \_ . \llbracket e_2 \rrbracket_{\Psi}^y y & \text{if } \Psi = \emptyset; \\ \lambda \_ . \llbracket e_2 \rrbracket_{\Psi}^y y, \lambda x . \text{inr } x & \text{if } \Psi \neq \emptyset. \end{cases} \)

**Example.** The first Scala example from §1 may be recast in \( \lambda^{\text{URAL}} \) (with references, pairs, and integer division) as follows:

\[ \lambda z_1 z_2 . \text{pair } (\text{ref } (z_1 / z_2)) (\text{ref } (z_2 / z_1)) \]

Let us assume the following (monomorphic, for brevity) types for the operations:

\[ \cdot : U(\text{int } \otimes_0 U(\text{int } \{ \text{DivBy0} \} \cup \text{intref})) \]

\[ \text{ref} : U(\text{int } \otimes_0 \text{intref}) \]

\[ \text{pair} : U(\text{intref } \otimes_0 U(\text{intref } \otimes_0 \text{intref})) \]

To type the application of term \( \text{pair } (\text{ref } (z_1 / z_2)) \) to term \( \text{ref } (z_2 / z_1) \), according to premise (6) of rule C-T-APP, the effect of the operator must be bounded by the qualifier of the type of the operand. The effect of the operator, \( \text{pair } (\text{ref } (z_1 / z_2)) \), is \( \{ \text{DivBy0} \} \), based on the type of \( / \); the type of the operand, \( \text{ref } (z_2 / z_1) \), is \( \text{intref} \). But \( \not \vdash \{ \text{DivBy0} \} \geq L \) is not derivable—a term that can raise an exception does not necessarily treat it context linearly—so the original code has a type error in \( \lambda^{\text{URAL}}(\epsilon) \).

We can repair the example, as we did in §1, by explicitly ordering the effects so that both divisions happen before any references are allocated:

\[ \lambda z_1 z_2 . (\lambda x_1 x_2 . \text{pair } (\text{ref } x_1) (\text{ref } x_2)) (z_1 / z_2) (z_2 / z_1) \]

Term \( \lambda x_1 x_2 . \text{pair } (\text{ref } x_1) (\text{ref } x_2) \) has an unlimited type:

\[ U(\text{int } \otimes_0 U(\text{int } \otimes_0 U(\text{intref } \otimes_0 \text{intref}))) \]

Thus, it does not matter that its argument, \( z_1 / z_2 \), has non-trivial effect. Similarly, because the codomain of that type is unlimited, it is permissible that the second argument, \( z_2 / z_1 \), has non-trivial effect as well. Thus, the repaired example is typeable in \( \lambda^{\text{URAL}}(\epsilon) \).

**Type safety.** To prove type safety for \( \lambda^{\text{URAL}}(\epsilon) \) extended with exceptions, we define the translation parameter as follows:

\[ \llbracket \tau, \Psi \rrbracket_{X} = \llbracket \tau, \Psi^* \rrbracket_{X}^+ = L(\text{exn } \oplus \tau) \]

\[ \text{done}_x = \lambda x . \text{inr } x \]

\[ \Psi^* = \begin{cases} L & \text{if } \Psi = \emptyset \\ A & \text{if } \Psi \neq \emptyset \end{cases} \]

**Theorem 6.3 (Exception effect properties).** Exception effects \( (X, \emptyset, \cup) \) satisfy Properties 1–5.

The proofs of theorems in this section appear in the extended version of this paper, available at www.ccs.neu.edu/~tov/pubs/substructural-control.

## 7. Conclusion

We began this study with the desire to add linear types to Alms, a general-purpose programming language with affine types and exceptions. The treatment of exceptions in §6.3 points the way toward that goal. One question that remains, however, concerns the pragmatics of checked exceptions in a higher-order language such as Alms, where latent exception effects are likely to appear on many function arrows. We believe that with appropriate defaults most function arrows will not require annotation, but more research is required in that direction.

Another potential direction for future research is to consider how other control effects fit into our general framework. We suspect that some control operators common to imperative languages, such as return, break, and goto, absent first-class labels, would be straightforward. More exotic forms of control may be harder. Some control operators, such as shift0, are very difficult to type even in a simpler setting (Kiselyov and Shan 2007), which is why have not considered them. Others, such as Felleisen’s prompt and control (1988) are probably tractable with a more expressive version of our generic type system, because effects need to reflect not only how an expression treats its continuation, but how a continuation, if captured and reinvoked, treats its new continuation.

For the cases we consider, however, \( \lambda^{\text{URAL}}(\epsilon) \) provides a simple and generic framework for integrating substructural types and control effects. We have shown that our type system for \( \lambda^{\text{URAL}}(\epsilon) \) is sound provided that the particular instantiation of control effects meets several criteria, and we have exhibited three instances of control effects that meet these criteria. We contend that this provides a solid grounding for the extension of realistic substructural programming languages with control effects.

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