

SUBJECT REDUCTION FOR PURE TYPE SYSTEMS

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ABSTRACT. Following [SU06], we give a detailed proof of *subject reduction* for arbitrary *pure type systems*, which abstract many of the basic constructs found in, say, the simply-typed λ -calculus (λ_{\rightarrow}), the polymorphic λ -calculus (λ_2), the λ -calculus with type constructors (λ_{ω}), and the λ -calculus with dependent types ($\lambda_{\mathbf{P}}$).

Introduction. Subject reduction is a crucial property of a type system that guarantees its ‘computational consistency’ by ensuring that reductions of a well-typed expression remains well-typed, and which supports the slogan that ‘well-typed programs do not go wrong’. It is thus desirable that we can prove it uniformly across many different type systems, and this is the goal of the present note.

To this end, we start from the beginning¹ with the *simply-typed λ -calculus* λ_{\rightarrow} , in which we prove subject reduction. We then progress to more complicated type systems (in particular, λ_2 , λ_{ω} , and $\lambda_{\mathbf{P}}$) to illustrate some concepts not present in λ_{\rightarrow} , and along the way, we also mention the *λ -cube* to provide some motivation for *pure type systems*, which abstract the constructs in all of the previous systems. Finally, we prove subject reduction for pure type systems. We will not discuss any of these systems in length, but refer the interested reader to [SU06] for general type theory and [Bar91] for actual applications of pure type systems.

1. THE SIMPLY-TYPED λ -CALCULUS: λ_{\rightarrow}

Throughout, fix a countably infinite set V , whose element we call (*propositional/ λ -variables*).

Definition 1.1. A *simple type* is a propositional formula in the language $\{\rightarrow\}$; i.e., defined by the grammar $\tau := x \mid \tau \rightarrow \tau$ where $x \in V$. We let Φ_{\rightarrow} denote the set of simple types.

Definition 1.2. A λ -*term* is a string defined by the grammar² $M := x \mid M M \mid (\lambda x^{\tau} M)$, where $\tau \in \Phi_{\rightarrow}$. We denote by Λ the set of λ -terms. The set of *free variables* of a λ -term M is defined inductively by

$$FV(x) := \{x\}, \quad FV(\lambda x^{\tau} M) := FV(M) \setminus \{x\}, \quad FV(M N) := FV(M) \cup FV(N).$$

Remark 1.3. We always consider λ -terms under α -conversion. Basically, we can freely change the bound variable x in λx without modifying the term, but see [SU06, Section 1.2] for the formal definition.

Definition 1.4. Let $M, N \in \Lambda$ and fix $x \in FV(M)$. The *substitution* of N for x in M , written $M[N/x]$, is the λ -term defined by induction on M ; below, $y \neq x$ and $y \notin FV(N)$.

$$x[N/x] := N, \quad y[N/x] := y, \quad (P Q)[N/x] := P[N/x] Q[N/x], \quad (\lambda y^{\tau} P)[N/x] := \lambda y^{\tau}. P[N/x].$$

Definition 1.5. A *context* is a finite set $\Gamma := \{x_1 : \tau_1, \dots, x_n : \tau_n\}$, where $x_i \in V$ are pairwise-distinct and each $\tau_i \in \Phi_{\rightarrow}$; that is, $\Gamma : V \rightarrow \Phi_{\rightarrow}$ is a partial function, so we write $\Gamma(x) = \tau$ for $(x : \tau) \in \Gamma$ and we let

$$\text{dom } \Gamma := \{x \in V : \Gamma(x) = \tau \text{ for some } \tau \in \Phi_{\rightarrow}\} \quad \text{and} \quad \text{im } \Gamma := \{\tau \in \Phi_{\rightarrow} : \Gamma(x) = \tau \text{ for some } x \in V\}.$$

A *judgement* is a triple $\Gamma \vdash M : \tau$ consisting of a context Γ , a λ -term M , and a simple type τ .

Definition 1.6. We say that a judgement $\Gamma \vdash M : \tau$ is *derivable in λ_{\rightarrow}* if there is a finite tree of judgements rooted at $\Gamma \vdash M : \tau$, whose leaves are instances of VAR, and such that the children of each internal node is obtained from the rules ABS or APP read bottom-up.

$$\frac{}{\Gamma, x : \tau \vdash x : \tau} \text{VAR} \quad \frac{\Gamma, x : \sigma \vdash M : \tau}{\Gamma \vdash (\lambda x^{\sigma} M) : \sigma \rightarrow \tau} \text{ABS} \quad \frac{\Gamma \vdash M : \sigma \rightarrow \tau \quad \Gamma \vdash N : \sigma}{\Gamma \vdash (M N) : \tau} \text{APP}$$

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¹As Professor Pientka would say: ‘We’ll start slow’.

²Sometimes, people write $\lambda x : \tau M$ instead of $\lambda x^{\tau} M$, but we find the former too hard to parse.

The rules VAR and ABS can only be applied when $x \notin \text{dom } \Gamma$. We assert $\Gamma \vdash M : \tau$ if it is derivable.

Lemma 1.7 (Generation Lemma 1). *Suppose that $\Gamma \vdash M : \tau$.*

- (1) *If $M = x$, then $\Gamma(x) = \tau$.*
- (2) *If $M = PQ$, then $\Gamma \vdash P : \sigma \rightarrow \tau$ and $\Gamma \vdash Q : \sigma$ for some $\sigma \in \Phi_{\rightarrow}$.*

Proof. Since the root of the derivation tree for $\Gamma \vdash M : \tau$ determines the shape of M , we see that (1) follows from VAR and (2) follows from APP. ■

Lemma 1.8 (Variable Renaming). *If $\Gamma, x : \tau \vdash M : \sigma$ and $y \notin \text{dom } \Gamma \cup \{x\}$, then $\Gamma, y : \tau \vdash M[y/x] : \sigma$.*

Proof. By induction on the length of M . If $M = x$, then $\tau = \sigma$ and $M[y/x] = y$, and $\Gamma, y : \tau \vdash y : \sigma$ by VAR. If $M = z$ and $z \neq x$, then $M[y/x] = z$. Note that $\Gamma(z) = \sigma$ by Lemma 1.7.1, so $\Gamma, y : \tau \vdash z : \sigma$ by VAR.

If $M = PQ$, then by Lemma 1.7.2, we have $\Gamma, x : \tau \vdash P : \rho \rightarrow \sigma$ and $\Gamma, x : \tau \vdash Q : \rho$ for some $\rho \in \Phi_{\rightarrow}$. By induction, we have $\Gamma, y : \tau \vdash P[y/x] : \rho \rightarrow \sigma$ and $\Gamma, y : \tau \vdash Q[y/x] : \rho$, on which APP gives the desired.

If $M = \lambda z^\rho N$, then $\Gamma, x : \tau \vdash \lambda z^\rho N : \sigma$ is obtained by ABS, so it is of the form $\Gamma, x : \tau, w : \rho \vdash P : \eta$ for some $\eta \in \Phi_{\rightarrow}$ and $w, P \in \Lambda$ such that $\lambda z^\rho N = \lambda w^\rho P$ and $\sigma = \rho \rightarrow \eta$. Up to α -conversion, we can choose w so that $w \neq y$. Then, since $|P| = |N| < |M|$, we have by induction that $\Gamma, y : \tau, w : \rho \vdash P[y/x] : \eta$, on which ABS gives $\Gamma, y : \tau \vdash \lambda w^\rho P[y/x] : \sigma$. Now, $\lambda w^\rho P[y/x] = (\lambda w^\rho P)[y/x] = (\lambda z^\rho N)[y/x] = M[y/x]$. ■

Lemma 1.9 (Generation Lemma 2). *If $\Gamma \vdash \lambda x^\sigma M : \tau$ and $x \notin \text{dom } \Gamma$, then $\tau = \sigma \rightarrow \rho$ and $\Gamma, x : \sigma \vdash N : \rho$ for some $\rho \in \Phi_{\rightarrow}$.*

Proof. As in the above proof, there exist $\rho \in \Phi_{\rightarrow}$ and $y, N \in \Lambda$ such that $\Gamma, y : \sigma \vdash N : \rho$, $\lambda x^\sigma M = \lambda y^\sigma N$, and $\tau = \sigma \rightarrow \rho$. If $x = y$, we are done; otherwise, we have $N = M[y/x]$, so $\Gamma, y : \sigma \vdash M[y/x] : \rho$, and finally substituting x for y gives $\Gamma, x : \sigma \vdash M : \rho$ by Lemma 1.8, as desired. ■

Lemma 1.10 (Change of Context). *If $\Gamma \vdash M : \tau$ and $\Gamma(x) = \Gamma'(x)$ for all $x \in FV(M)$, then $\Gamma' \vdash M : \tau$.*

Proof. By induction on M . If $M = x$, then $\Gamma'(x) = \Gamma(x) = \tau$ by Lemma 1.7.1, and hence $\Gamma' \vdash x : \tau$ by VAR. If $M = PQ$, then by Lemma 1.7.2, we have $\Gamma \vdash P : \sigma \rightarrow \tau$ and $\Gamma \vdash Q : \sigma$ for some $\sigma \in \Phi_{\rightarrow}$. By induction, we see that $\Gamma' \vdash P : \sigma \rightarrow \tau$ and $\Gamma' \vdash Q : \sigma$, on which APP gives $\Gamma' \vdash M : \tau$. Lastly, if $M = \lambda x^\sigma N$, we can choose $x \notin \text{dom } \Gamma \cup \text{dom } \Gamma'$, so that $\tau = \sigma \rightarrow \rho$ and $\Gamma, x : \sigma \vdash N : \rho$ by Lemma 1.9. By induction, we see that $\Gamma', x : \sigma \vdash N : \rho$, on which ABS gives the desired as $\Gamma' \vdash M : \tau$. ■

We can think of the Change of Context lemma as a generalizing weakening as we can take $\Gamma' := \Gamma, y : \sigma$ for $y \notin FV(M)$, and this is exactly how we use it below.

Lemma 1.11 (Substitution Lemma). *If $\Gamma, x : \sigma \vdash M : \tau$ and $\Gamma \vdash N : \sigma$, then $\Gamma \vdash M[N/x] : \tau$.*

Proof. By induction on M . If $M = y$ and $x \neq y$, then $\Gamma(y) = \tau$ and $M[N/x] = y$, so that $\Gamma \vdash y : \tau$ by VAR. If $x = y$, then $\Gamma(x) = \sigma$ and $M[N/x] = N$, so $\tau = \sigma$ and $\Gamma \vdash N : \sigma$ by assumption. If $M = PQ$, then by Lemma 1.7.2, we have $\Gamma, x : \sigma \vdash P : \rho \rightarrow \tau$ and $\Gamma, x : \sigma \vdash Q : \rho$ for some $\rho \in \Phi_{\rightarrow}$. By induction, we see that $\Gamma \vdash P[N/x] : \rho \rightarrow \tau$ and $\Gamma \vdash Q[N/x] : \rho$, on which APP gives $\Gamma \vdash M[N/x] : \tau$.

Lastly, if $M = \lambda y^\eta M'$ where $y \notin \text{dom } \Gamma \cup \{x\} \cup FV(N)$, then by Lemma 1.9, there is some $\rho \in \Phi_{\rightarrow}$ such that $\tau = \eta \rightarrow \rho$ and $\Gamma, x : \sigma, y : \eta \vdash M' : \rho$. By Lemma 1.10, we can weaken $\Gamma \vdash N : \sigma$ to $\Gamma, y : \eta \vdash N : \sigma$, so by induction³ we have $\Gamma, y : \eta \vdash M'[N/x] : \rho$, and we can apply ABS to get $\Gamma \vdash M[N/x] : \tau$. ■

Definition 1.12. A relation \succ on Λ is *compatible* if for any $M, N \in \Lambda$ with $M \succ N$, we have $MP \succ NP$ and $PM \succ PN$ for each $P \in \Lambda$, and $\lambda x^\tau M \succ \lambda x^\tau N$ for each $x \in V$ and $\tau \in \Phi_{\rightarrow}$.

Definition 1.13. The least compatible relation \rightarrow_β on Λ such that $(\lambda x^\tau M)N \rightarrow_\beta M[N/x]$ for all $M, N \in \Lambda$ is called β -reduction. We say that $(\lambda x^\tau M)N$ is a β -redex and that $M[N/x]$ arises by *contracting* the redex.

Notation 1.14. For any relation \rightarrow_\bullet on a set X , we let \rightarrow_\bullet^+ denote the transitive closure, let \rightarrow_\bullet denote the transitive and reflexive closure, and let $=_\bullet$ denote the least equivalence relation containing \rightarrow_\bullet .

Theorem 1.15 (Subject Reduction). *If $\Gamma \vdash M : \tau$ and $M \rightarrow_\beta N$, then $\Gamma \vdash N : \tau$.*

Proof. If $M = (\lambda x^\sigma P)Q$ and $N = P[Q/x]$ for some $x \notin \text{dom } \Gamma$, then we have $\Gamma, x : \sigma \vdash P : \tau$ and $\Gamma \vdash Q : \sigma$ by Lemma 1.7.2 and 1.9, so $\Gamma \vdash N : \tau$ by Lemma 1.11. The general case follows by induction on \rightarrow_β . ■

³Note that our contexts are unordered, so we have exchange implicitly.

2. THE POLYMORPHIC λ -CALCULUS: $\lambda 2$

Throughout, fix two disjoint countable sets V and V_t of variables and *type-variables*.

Definition 2.1. A *polymorphic type* is a propositional formula in the language $\{\rightarrow, \forall\}$ over V_τ , i.e., defined by the grammar $\tau := x \mid \tau \rightarrow \tau \mid \forall p \tau$ where $x \in V$ and $p \in V_t$. Let Φ_2 denote the set of polymorphic types.

Definition 2.2. A *polymorphic term* is either a λ -term, a *polymorphic abstraction* $\Lambda p M$ for $p \in V_t$, or a *type application* $M \tau$ for $\tau \in \Phi_2$. That is, $M := x \mid M M \mid \lambda x^\tau M \mid \Lambda p M \mid M \tau$ where $\tau \in \Phi_2$ and $p \in V_t$. We denote by Λ_2 the set of all polymorphic terms. The set of *free variables* of a polymorphic term M and a polymorphic type τ is defined inductively by extending FV from before, and letting

$$\begin{aligned} FV(\Lambda p M) &:= FV(M) \setminus \{p\}, & FV(M \tau) &:= FV(M) \cup FV(\tau) \\ FV(\tau \rightarrow \sigma) &:= FV(\tau) \cup FV(\sigma), & FV(\forall p \tau) &:= FV(\tau) - \{p\}. \end{aligned}$$

Definition 2.3. Let $\tau, \sigma \in \Phi_2$ and fix $p \in FV(\tau)$. The *substitution* of σ for p in τ , written $\tau[\sigma/p]$, is the polymorphic type defined by induction on τ ; below, $q \neq p$ and $q \notin FV(\sigma)$.

$$p[\sigma/p] := \sigma, \quad q[\sigma/p] := q, \quad (\tau_1 \rightarrow \tau_2)[\sigma/p] := \tau_1[\sigma/p] \rightarrow \tau_2[\sigma/p], \quad (\forall q \tau)[\sigma/p] := \forall q \tau[\sigma/p].$$

Definition 2.4. For $M, N \in \Lambda_2$ and $x \in FV(M)$, we extend the substitution $M[N/x]$ by letting $(\Lambda p M)[N/x] := \Lambda p M[N/x]$ for $p \notin FV(N)$ and $(M \tau)[N/x] := M[N/x] \tau$. For $p \in FV(M)$ and $\sigma \in \Phi_2$, we define the *substitution* of σ for p in M , written $M[\sigma/p]$, as the polymorphic term below, where $q \notin FV(\sigma) \cup \{p\}$.

$$\begin{aligned} x[\sigma/p] &:= x, & (P Q)[\sigma/p] &:= P[\sigma/p] Q[\sigma/p], & (\lambda x^\tau M)[\sigma/p] &:= \lambda x^{\tau[\sigma/p]} M[\sigma/p], \\ (M \tau)[\sigma/p] &:= M[\sigma/p] \tau[\sigma/p], & (\Lambda q M)[\sigma/p] &:= \Lambda q M[\sigma/p]. \end{aligned}$$

Lemma 2.5.

Theorem 2.6 (Subject Reduction for $\lambda 2$).

3. THE λ -CALCULUS WITH TYPE CONSTRUCTORS: $\lambda \omega$

Definition 3.1.

Lemma 3.2.

Theorem 3.3 (Subject Reduction for $\lambda \omega$).

4. THE λ -CALCULUS WITH DEPENDENT TYPES: $\lambda \mathbf{P}$

Definition 4.1.

Lemma 4.2.

Theorem 4.3 (Subject Reduction for $\lambda \mathbf{P}$).

5. THE λ -CUBE AND BEYOND: PURE TYPE SYSTEMS

Definition 5.1.

Lemma 5.2.

Theorem 5.3 (Subject Reduction for Pure Type Systems).

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