Proofs as Programs Summer School
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Type Systems

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Lecture 1: Simple Type Theory

Simplest system: $\lambda\!\!\rightarrow$ just arrow types

$$\mathsf{Typ} := \mathsf{TVar} \mid (\mathsf{Typ}\!\rightarrow\!\mathsf{Typ})$$

- Examples: $(\alpha\!\rightarrow\!\beta)\!\rightarrow\!\alpha$, $(\alpha\!\rightarrow\!\beta)\!\rightarrow\!((\beta\!\rightarrow\!\gamma)\!\rightarrow\!(\alpha\!\rightarrow\!\gamma))$
- Brackets associate to the right and outside brackets are omitted:
  $(\alpha\!\rightarrow\!\beta)\!\rightarrow\!(\beta\!\rightarrow\!\gamma)\!\rightarrow\!\alpha\!\rightarrow\!\gamma$
- Types are denoted by $\sigma, \tau, \ldots$.

Terms:

- typed variables $x_1^\sigma, x_2^\sigma, \ldots$, countably many for every σ.
- application: if $M : \sigma\!\rightarrow\!\tau$ and $N : \sigma$, then $(MN) : \tau$
- abstraction: if $P : \tau$, then $(\lambda x^\sigma.P) : \sigma\!\rightarrow\!\tau$

Examples:

$$\lambda x^{\sigma}.\lambda y^{\tau}.x \ : \ \sigma{\to}\tau{\to}\sigma$$
$$\lambda x^{\alpha\to\beta}.\lambda y^{\beta\to\gamma}.\lambda z^{\alpha}.y(xz) \ : \ (\alpha{\to}\beta){\to}(\beta{\to}\gamma){\to}\alpha{\to}\gamma$$
$$\lambda x^{\alpha}.\lambda y^{(\beta\to\alpha)\to\alpha}.y(\lambda z^{\beta}.x)) \ : \ \alpha{\to}((\beta{\to}\alpha)\alpha){\to}\alpha$$

For every type there is a term of that type:

$$x^{\sigma} : \sigma$$

Not for every type there is a closed term of that type:

$(\alpha{\to}\alpha){\to}\alpha$ is not inhabited

Typed Terms versus Type Assignment:

- With typed terms also called typing à la Church, we have terms with type information in the λ-abstraction
  As a consequence:
  - Terms have unique types,
  - The type is directly computed from the type info in the variables.
- With typed assignment also called typing à la Curry, we assign types to untyped λ-terms
  As a consequence:
  - Terms do not have unique types,
  - A principal type can be computed using unification.

Examples:

- Typed Terms:

$$\lambda x^{\alpha}.\lambda y^{(\beta\to\alpha)\to\alpha}.y(\lambda z^{\beta}.x))$$

  has only the type $\alpha\to((\beta\to\alpha)\to\alpha)\to\alpha$

- Type Assignment:

$$\lambda x.\lambda y.y(\lambda z.x))$$

  can be given the types

  - $\alpha\to((\beta\to\alpha)\to\alpha)\to\alpha$
  - $\alpha\to((\beta\to\alpha)\to\gamma)\to\gamma$
  - $(\alpha\to\alpha)\to((\beta\to\alpha\to\alpha)\to\gamma)\to\gamma$
  - ...

  with $\alpha\to((\beta\to\alpha)\to\gamma)\to\gamma$ being the principal type

Example of computing a principle type:

$$\lambda x.\lambda y.y(\lambda z.yx)$$

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$$\alpha := \gamma \rightarrow \delta, \beta := (\gamma \rightarrow \delta) \rightarrow \epsilon, \delta := \epsilon$$

4. The principal type of $\lambda x.\lambda y.y(\lambda z.yx)$ is now

$$(\gamma \rightarrow \epsilon) \rightarrow ((\gamma \rightarrow \epsilon) \rightarrow \epsilon) \rightarrow \epsilon$$

Typical problems one would like to have an algorithm for:

$M : \sigma ?$	Type Checking Problem	TCP
$M : ?$	Type Synthesis Problem	TSP
$? : \sigma$	Type Inhabitation Problem (by a closed term)	TIP

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Remarks:

- TCP and TSP are (usually) equivalent:
  To solve $MN : \sigma$, one has to solve $N :?$ (and if this gives answer τ, solve $M : \tau{\to}\sigma$).
- For Curry systems, TCP and TSP soon become undecidable if we go beyond $\lambda{\to}$.
- TIP is undecidable for most extensions of $\lambda{\to}$, as it corresponds to provability in some logic.

From now on we focus on the Church formulation of simple type theory:

terms with type information.

Formulation with contexts to declare the free variables:

$$x_1 : \sigma_1, x_2 : \sigma_2, \ldots, x_n : \sigma_n$$

is a context, usually denoted by Γ.

Derivation rules of $\lambda\!\rightarrow$:

$$\frac{x{:}\sigma \in \Gamma}{\Gamma \vdash x : \sigma} \qquad \frac{\Gamma \vdash M : \sigma{\rightarrow}\tau \;\; \Gamma \vdash N : \sigma}{\Gamma \vdash MN : \tau} \qquad \frac{\Gamma, x{:}\sigma \vdash P : \tau}{\Gamma \vdash \lambda x{:}\sigma.P : \sigma{\rightarrow}\tau}$$

$\Gamma \vdash_{\lambda\rightarrow} M : \sigma$ if there is a derivation using these rules with conclusion $\Gamma \vdash M : \sigma$

Formulas-as-Types (Curry, Howard):

There are two readings of a judgement $M : \sigma$

1. term as algorithm/program, type as specification:
   M is a function of type σ
2. type as a proposition, term as its proof:
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- There is a one-to-one correspondence between
  - typable terms in $\lambda{\to}$
  - derivations in minimal proposition logic
- The judgement

$$x_1 : \tau_1, x_2 : \tau_2, \ldots, x_n : \tau_n \vdash M : \sigma$$

  can be read as

  M is a proof of σ from the assumptions $\tau_1, \tau_2, \ldots, \tau_n$.

Example

$$\dfrac{\dfrac{\dfrac{\dfrac{[\alpha\to\beta\to\gamma]^3 \quad [\alpha]^1}{\beta\to\gamma} \qquad \dfrac{[\alpha\to\beta]^2 \quad [\alpha]^1}{\beta}}{\gamma}}{\alpha\to\gamma}\,1}{(\alpha\to\beta)\to\alpha\to\gamma}\,2}{(\alpha\to\beta\to\gamma)\to(\alpha\to\beta)\to\alpha\to\gamma}\,3 \quad\simeq\quad \begin{array}{c}\lambda x{:}\alpha\to\beta\to\gamma.\lambda y{:}\alpha\to\beta.\lambda z{:}\alpha.xz(yz)\\ :(\alpha\to\beta\to\gamma)\to(\alpha\to\beta)\to\alpha\to\gamma\end{array}$$

Example

$$\dfrac{\dfrac{\dfrac{[\alpha\to\beta\to\gamma]^3\ \ [\alpha]^1}{\beta\to\gamma}\qquad\dfrac{[\alpha\to\beta]^2\ \ [\alpha]^1}{\beta}}{\dfrac{\gamma}{\alpha\to\gamma}\,1}\,2}{(\alpha\to\beta)\to\alpha\to\gamma}\,3}{(\alpha\to\beta\to\gamma)\to(\alpha\to\beta)\to\alpha\to\gamma}$$

$$\simeq\quad \lambda x{:}\alpha\to\beta\to\gamma.\lambda y{:}\alpha\to\beta.\lambda z{:}\alpha.xz(yz)$$
$$: (\alpha\to\beta\to\gamma)\to(\alpha\to\beta)\to\alpha\to\gamma$$

$$\dfrac{\dfrac{\dfrac{[x:\alpha\to\beta\to\gamma]^3\ \ [z:\alpha]^1}{xz:\beta\to\gamma}\qquad\dfrac{[y:\alpha\to\beta]^2\ \ [z:\alpha]^1}{yz:\beta}}{xz(yz):\gamma}\,1}{\lambda z{:}\alpha.xz(yz):\alpha\to\gamma}\,2}{\lambda y{:}\alpha\to\beta.\lambda z{:}\alpha.xz(yz):(\alpha\to\beta)\to\alpha\to\gamma}\,3$$
$$\lambda x{:}\alpha\to\beta\to\gamma.\lambda y{:}\alpha\to\beta.\lambda z{:}\alpha.xz(yz):(\alpha\to\beta\to\gamma)\to(\alpha\to\beta)\to\alpha\to\gamma$$

Computation:

- β-reduction: $(\lambda x{:}\sigma.M)P \longrightarrow_\beta M[P/x]$
- η-reduction: $\lambda x{:}\sigma.Mx \longrightarrow_\eta M$ if $x \notin \mathsf{FV}(M)$

Cut-elimination in minimal logic $=$ β-reduction in $\lambda{\to}$.

$$\dfrac{\begin{array}{c}[\sigma]^1\\ \mathcal{D}_1\\ \tau\end{array}}{\dfrac{\sigma{\to}\tau \quad 1 \qquad \dfrac{\mathcal{D}_2}{\sigma}}{\tau}} \rightsquigarrow \begin{array}{c}\mathcal{D}_2\\ \sigma\\ \mathcal{D}_1\\ \tau\end{array}$$

$$\dfrac{\begin{array}{c}[x:\sigma]^1\\ \mathcal{D}_1\\ M:\tau\end{array}}{\dfrac{\lambda x{:}\sigma.M : \sigma{\to}\tau \quad 1 \qquad \dfrac{\mathcal{D}_2}{P:\sigma}}{(\lambda x{:}\sigma.M)P : \tau}} \rightsquigarrow \begin{array}{c}\mathcal{D}_2\\ P:\sigma\\ \mathcal{D}_1\\ M[P/x]:\tau\end{array}$$

Properties of $\lambda\!\rightarrow$.

- Uniqueness of types
  If $\Gamma \vdash M : \sigma$ and $\Gamma \vdash M : \tau$, then $\sigma = \tau$.
- Subject Reduction
  If $\Gamma \vdash M : \sigma$ and $M \longrightarrow_{\beta\eta} N$, then $\Gamma \vdash N : \sigma$.
- Strong Normalization
  If $\Gamma \vdash M : \sigma$, then all $\beta\eta$-reductions from M terminate.

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- Strong Normalization
  If $\Gamma \vdash M : \sigma$, then all $\beta\eta$-reductions from M terminate.
- Substitution property
  If $\Gamma, x : \tau, \Delta \vdash M : \sigma$, $\Gamma \vdash P : \tau$, then $\Gamma, \Delta \vdash M[P/x] : \sigma$.
- Thinning
  If $\Gamma \vdash M : \sigma$ and $\Gamma \subseteq \Delta$, then $\Delta \vdash M : \sigma$.
- Strengthening
  If $\Gamma, x : \tau \vdash M : \sigma$ and $x \notin \mathsf{FV}(M)$, then $\Gamma \vdash M : \sigma$.

Strong Normalization of β for $\lambda{\to}$.

Note:

- Terms may get larger under reduction
- Redexes may get multiplied under reduction.

Definition

- $[\![\alpha]\!] := \mathsf{Term}(\alpha) \cap \mathsf{SN}$.
- $[\![\sigma{\to}\tau]\!] := \{M : \sigma{\to}\tau | \forall N \in [\![\sigma]\!](MN \in [\![\tau]\!])\}$.

Lemma (all by induction on σ)

- $[\![\sigma]\!] \subseteq \mathsf{SN}$
- $x^\sigma \in [\![\sigma]\!]$
- If $M \in [\![\sigma]\!]$, $N \in [\![\tau]\!]$, $M[N/x] \in \mathsf{SN}$, then $M[N/x] \in [\![\sigma]\!]$.

Proposition

$$M : \sigma \Rightarrow M \in [\![\sigma]\!]$$

Corollary $\lambda\!\!\rightarrow$ is SN