Various Approaches to Computing Moduli of Continuity

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The Continuity Principles

In Brouwerian intuitionistic mathematics,

- all functions $\mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ are continuous, i.e.

$$\forall(f : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}).\forall(\alpha : \mathbb{N}^{\mathbb{N}}).\exists(m : \mathbb{N}).\forall(\beta : \mathbb{N}^{\mathbb{N}}).\,(\alpha =_m \beta \to f\alpha = f\beta)$$

- all functions $\mathbf{2}^{\mathbb{N}} \to \mathbb{N}$ are uniformly continuous, i.e.

$$\forall(f : \mathbf{2}^{\mathbb{N}} \to \mathbb{N}).\exists(m : \mathbb{N}).\forall(\alpha, \beta : \mathbf{2}^{\mathbb{N}}).\,(\alpha =_m \beta \to f\alpha = f\beta)$$

where B^A stands for $A \to B$, and $\alpha =_m \beta$ for $\forall(i < m).\alpha_i = \beta_i$.

Continuity of System T-Definable Functions

Theorem.

- All functions $\mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ definable in Gödel's System T are continuous.
- And their restriction to $2^{\mathbb{N}}$ are uniformly continuous.

This talk is to give a brief overview of various proofs of this fact, with a focus on their computational content, i.e., how moduli of continuity are computed.

Why am I interested in it?

- Relate different proofs via their computational content
- Generalize the methods for other purposes

But I don't know which proof is the first. And I don't know any applications.

Moduli of Continuity

A function $f : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ is continuous if

$$\forall(\alpha : \mathbb{N}^{\mathbb{N}}).\exists(m : \mathbb{N}).\forall(\beta : \mathbb{N}^{\mathbb{N}}).\, (\alpha =_m \beta \to f\alpha = f\beta)\,.$$

We call m a modulus of continuity of f at α.

A function $M : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ is called a modulus of continuity of $f : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ if $M\alpha$ is the modulus of continuity of f at α for all $\alpha : \mathbb{N}^{\mathbb{N}}$, i.e.,

$$\forall(\alpha, \beta : \mathbb{N}^{\mathbb{N}}).\, (\alpha =_{M\alpha} \beta \to f\alpha = f\beta)\,.$$

We will explore various methods to compute moduli of continuity of functions that are definable in System T.

Continuity Proofs: Syntactic Approaches

Proving certain property by induction on T terms (without using models)

- A. S. Troelstra, editor. *Metamathematical investigation of intuitionistic arithmetic and analysis*. Springer-Verlag, Berlin, 1973.
- Ulrich Kohlenbach. Pointwise hereditary majorization and some applications. *Archive for Mathematical Logic*, 31(4):227–241, 1992.
- Thomas Powell. A functional interpretation with state. LICS'18, pp. 839–848, 2018.
- Chuangjie Xu. A Gentzen-style monadic translation of Gödel's System T. FSCD'20, pp. 30:1–30:17, 2020.

Continuity Proofs: Semantic Approaches

Operational semantics

- Thierry Coquand and Guilhem Jaber. A computational interpretation of forcing in type theory. In *Epistemology versus Ontology*, vol. 27, pp. 203–213. Springer Netherlands, 2012.

Denotational models

- Martín Escardó. Continuity of Gödel's system T functionals via effectful forcing. MFPS'13, Electronic Notes in Theoretical Computer Science, vol. 298, pp. 119–141, 2013.
- Sheaf models such as
  - Peter Johnstone. On a topological topos, *Proceedings of the London Mathematical Society*, s3-38:237–271, 1979.
  - Michael P. Fourman. Continuous truth I, non-constructive objects. Logic Colloquium '82, pp. 161–180. Elsevier, 1984.
  - Gerrit van der Hoeven and Ieke Moerdijk. Sheaf models for choice sequences. *Annals of Pure and Applied Logic*, 27(1):63–107, 1984.
  - Martín Escardó and Chuangjie Xu. A constructive manifestation of the Kleene–Kreisel continuous functionals. *Annals of Pure and Applied Logic*, 167(9):770–793, 2016.

Continuity Proofs: Computational Effects

- Andrej Bauer. Sometimes all functions are continuous. Blog. 2006.
- Vincent Rahli and Mark Bickford. A nominal exploration of intuitionism. CPP'16. 2016.
- Liron Cohen and Vincent Rahli. Realizing Continuity Using Stateful Computations. 2022.

Computing Moduli of Continuity: Evaluation Strategies

Call by name: [Escardó 2013], [Xu 2020], ...

Call by value: [Coquand&Jaber 2012], [Powell 2018], ...

Gödel's System T

We work with (the term language of) Gödel's System T in its λ-calculus form

$$\mathsf{T} \;\equiv\; \text{simply typed } \lambda\text{-calculus} \;+\; \mathsf{Nat} \;+\; \text{primitive recursor.}$$

It can be given by

$$\begin{array}{llcl} \textsf{Type} & \sigma, \tau & := & \mathsf{Nat} \mid \sigma \to \tau \\ \textsf{Term} & t, u & := & x \mid \lambda x.t \mid tu \mid 0 \mid \mathrm{succ} \mid \mathrm{rec}_\sigma \end{array}$$

with the following typing rules:

$$\frac{}{\Gamma, x : \sigma \vdash x : \sigma} \qquad \frac{\Gamma, x : \sigma \vdash t : \tau}{\Gamma \vdash \lambda x.t : \sigma \to \tau} \qquad \frac{\Gamma \vdash t : \sigma \to \tau \qquad \Gamma \vdash u : \sigma}{\Gamma \vdash tu : \tau}$$

$$\frac{}{\Gamma \vdash 0 : \mathsf{Nat}} \qquad \frac{}{\Gamma \vdash \mathrm{succ} : \mathsf{Nat} \to \mathsf{Nat}}$$

$$\frac{}{\Gamma \vdash \mathrm{rec}_\sigma : \sigma \to (\mathsf{Nat} \to \sigma \to \sigma) \to \mathsf{Nat} \to \sigma}$$

where the context Γ is a list of distinct typed variables $x : \sigma$.

Gödel's System T: Some Conventions

We refer to only the well-typed terms $\Gamma \vdash t : \tau$.

We may omit the context and write $t : \tau$ or t^τ or just t.

We may omit the type script and write rec.

We may write

- $\lambda x_1 x_2 \cdots x_n.t$ instead of $\lambda x_1.\lambda x_2.\cdots\lambda x_n.t$;
- $f(a_1, a_2, \cdots, a_n)$ instead of $(((f a_1) a_2) \cdots) a_n$;
- $n + 1$ instead of $\mathrm{succ}(n)$;
- τ^σ instead of $\sigma \to \tau$;

Gödel's System T: Example

Using the primitive recursor, we can for instance define the function

$$\max : \mathsf{Nat} \to \mathsf{Nat} \to \mathsf{Nat}$$

that returns the greater argument by

$$\max := \mathrm{rec}_{\mathsf{Nat}\to\mathsf{Nat}}\,(\lambda n.n,\ \lambda nf.\mathrm{rec}_{\mathsf{Nat}}(n+1, \lambda mg.fm+1))$$

One can easily verify that the usual defining equations of $\max$

$$\max(0,n) = n \quad \max(m,0) = m \quad \max(m+1,n+1) = \max(m,n)+1$$

using the computation rules of rec

$$\mathrm{rec}(a,f,0) = a \qquad \mathrm{rec}(a,f,n+1) = f(n, \mathrm{rec}(a,f,n)).$$

Gödel's System T: Standard Interpretation

System T can be modeled by any cartesian closed category with a natural numbers object.

In particular, we can interpret System T into the meta-language, where types are interpreted by

$$[\![\mathsf{Nat}]\!] := \mathbb{N}$$
$$[\![\sigma \to \tau]\!] := [\![\sigma]\!] \to [\![\tau]\!]$$

and terms $x_1 : \sigma_1, \cdots, x_n : \sigma_n \vdash t : \tau$ as functions $[\![\sigma_1]\!] \times \ldots \times [\![\sigma_n]\!] \to [\![\tau]\!]$ by recursion on t.

A function f is T-definable if we can fine a term t in T such $f = [\![t]\!]$.

When referring to a T-definable function, we required the term t to be given explicitly.

Computing Moduli of Continuity via Exception Handling

We extend System T with effects such as exceptions[1,2].

To compute the modulus of continuity of a pure $f : (\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat}$ at an input $\alpha : \mathsf{Nat} \to \mathsf{Nat}$, we

- generate an impure input β that
  - returns αi if $i < k$
  - throws an exception otherwise

  for some parameter k, and
- try to compute $f \beta$ from $k = 0$
  - if it throws an exception, we catch it and try with $k + 1$.

At some point no exception happens. Then we know that the current value of k is a modulus of continuity.

[1] `http://math.andrej.com/2006/03/27/sometimes-all-functions-are-continuous/`

[2] Vincent Rahli and Mark Bickford. A nominal exploration of intuitionism. CPP'16.

Computing Moduli of Continuity via Exception Handling (cont.)

Why does this procedure of computing k terminate?

All terms of System T are total.

- Any closed term of type Nat is evaluated to some numeral $\mathrm{succ}^n(0)$ in finite steps.
- The computation of $f\alpha$ terminates, meaning that only finite parts of α can be accessed by f.
- A big enough k can be reached so that $f\beta$ also terminates.

The procedure $\alpha \mapsto k$ is not a pure program, i.e., the modulus is not a T term.

It does not seem efficient.

Continuity via Denotational Semantics

Idea: Suppose we have a model $\mathcal{M}$.

$$\begin{tikzcd} f = [\![t]\!] & \sim & [\![t]\!]_{\mathcal{M}} & \Longrightarrow & f \text{ is continuous} \\ & t \arrow[ul, mapsto] \arrow[ur, mapsto] & & & \end{tikzcd}$$

- Interpret terms t by $[\![t]\!]_{\mathcal{M}}$ in the model $\mathcal{M}$.
- Relate the two interpretations with some logical relation $[\![t]\!] \sim [\![t]\!]_{\mathcal{M}}$ by induction on t.
- Derive continuity of $[\![t]\!]$ from the proof of $[\![t]\!] \sim [\![t]\!]_{\mathcal{M}}$.

Escardó's Dialogue Trees

The type $\tilde{\mathbb{N}}$ of Dialogue trees[3] (for natural numbers) is inductively generated by

$$\eta : \mathbb{N} \to \tilde{\mathbb{N}} \qquad \beta : (\mathbb{N} \to \tilde{\mathbb{N}}) \to \mathbb{N} \to \tilde{\mathbb{N}}$$

Dialogue trees are decoded with an oracle $\alpha : \mathbb{N}^{\mathbb{N}}$ as follows:

$$\begin{aligned}
&\mathrm{dialogue} : \tilde{\mathbb{N}} \to (\mathbb{N} \to \mathbb{N}) \to \mathbb{N} \\
&\mathrm{dialogue}\ (\eta\ n)\ \alpha = n \\
&\mathrm{dialogue}\ (\beta\ \Phi\ x)\ \alpha = \mathrm{dialogue}\ (\Phi(\alpha x))\ \alpha
\end{aligned}$$

One can construct a function $\Omega : \tilde{\mathbb{N}} \to \tilde{\mathbb{N}}$, called a generic sequence, that codes any concrete sequence α, i.e.,

$$\begin{tikzcd}
\tilde{\mathbb{N}} \arrow[r, "\Omega"] \arrow[d, "\mathrm{dialogue}(-,\alpha)"'] & \tilde{\mathbb{N}} \arrow[d, "\mathrm{dialogue}(-,\alpha)"] \\
\mathbb{N} \arrow[r, "\alpha"'] & \mathbb{N}
\end{tikzcd}$$

[3] Martín Escardó. Continuity of Gödel's system T functionals via effectful forcing. MFPS'13.

Continuity via Dialogue Trees

We interpret System T using Dialogue trees

$$[\![\mathsf{Nat}]\!]_{\mathcal{D}} := \tilde{\mathbb{N}}$$
$$[\![\sigma \to \tau]\!]_{\mathcal{D}} := [\![\sigma]\!]_{\mathcal{D}} \to [\![\tau]\!]_{\mathcal{D}}$$

(The interpretation of terms is omitted.)

Lemma. For all $f : (\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat}$, we have for all $\alpha : \mathbb{N}^{\mathbb{N}}$

$$[\![f]\!](\alpha) = \mathrm{dialogue}([\![f]\!]_{\mathcal{D}}(\Omega))(\alpha).$$

Lemma. For any dialogue tree d, its decodification $\mathrm{dialogue}(d) : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ is continuous.

Theorem. All T-definable function $\mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ are continuous.

Uniform Continuity

A function $f : 2^{\mathbb{N}} \to \mathbb{N}$ is uniformly continuous if there is an $m : \mathbb{N}$, called the modulus of uniform continuity, such that

$$\forall(\alpha, \beta : 2^{\mathbb{N}}). \, (\alpha =_m \beta \to f\alpha = f\beta) \, .$$

Goal: Use C-spaces[4] to show that all functions $2^{\mathbb{N}} \to \mathbb{N}$ that are definable in System T (extended with Booleans) are uniformly continuous.

The construction of C-spaces needs uniformly continuous endofunctions on $2^{\mathbb{N}}$.

A function $f : 2^{\mathbb{N}} \to 2^{\mathbb{N}}$ is uniformly continuous if

$$\forall(n : \mathbb{N}).\exists(m : \mathbb{N}).\forall(\alpha, \beta : 2^{\mathbb{N}}). \, (\alpha =_m \beta \to f\alpha =_n f\beta) \, .$$

Let C be the set of uniformly continuous maps $2^{\mathbb{N}} \to 2^{\mathbb{N}}$.

[4] Martín Escardó and Chuangjie Xu. A constructive manifestation of the Kleene–Kreisel continuous functionals. APAL, 167(9):770–793, 2016.

C-Spaces

A C-space is a set X equipped with a C-topology P, that is, a collection of maps $2^{\mathbb{N}} \to X$, called probes, satisfying the following conditions:

- All constant maps are in P.
- If $p \in P$ and $t : 2^{\mathbb{N}} \to 2^{\mathbb{N}}$ is uniformly continuous, then $p \circ t \in P$.
- For any $p_0, p_1 \in P$, the map $p : 2^{\mathbb{N}} \to X$ defined by $p(\alpha) = p_{\alpha_0}(\lambda i.\alpha_{i+1})$ is in P.

A C-continuous map from (X, P) to (Y, Q) is a map $f : X \to Y$ such that if $p \in P$ then $f \circ p \in Q$.

C-Spaces (cont.)

Theorem. The category of C-spaces is cartesian closed.

The C-space $(\mathbb{N}, P_{\mathbb{N}})$ a natural numbers object and $(2, P_2)$ the coproduct of the terminal object, where P_X is the set of uniformly continuous maps into X.

The exponent $(2, P_2)^{(\mathbb{N}, P_{\mathbb{N}})}$ is the internal Cantor space of C-spaces.

Lemma. The identity map on $2^{\mathbb{N}}$ is a probe on $(2, P_2)^{(\mathbb{N}, P_{\mathbb{N}})}$.

We denote this probe by Ω, i.e., the identity map with a continuity proof.

Yoneda Lemma. If $f : (2, P_2)^{(\mathbb{N}, P_{\mathbb{N}})} \to (X, P)$ is C-continuous then $f \circ \Omega \in P$.

Note that f is (pointwise) equal to $f \circ \Omega$.

(The Yoneda lemma actually says more than above.)

Uniform Continuity via C-Spaces

We interpret System T in C-spaces by

$$[\![\mathsf{Nat}]\!]_{\mathcal{C}} := (\mathbb{N}, P_{\mathbb{N}})$$

$$[\![\mathsf{Bool}]\!]_{\mathcal{C}} := (\mathbb{2}, P_{\mathbb{2}})$$

$$[\![\sigma \to \tau]\!]_{\mathcal{C}} := [\![\tau]\!]_{\mathcal{C}}^{[\![\sigma]\!]_{\mathcal{C}}}$$

and terms by C-continuous maps.

Lemma. For any closed term $f : (\mathsf{Nat} \to \mathsf{Bool}) \to \mathsf{Nat}$ in System T, its interpretation $[\![f]\!]_{\mathcal{C}} : (\mathbb{2}, P_{\mathbb{2}})^{(\mathbb{N}, P_{\mathbb{N}})} \to (\mathbb{N}, P_{\mathbb{N}})$ is a C-continuous map.

We have $[\![f]\!]$ pointwise equal to $[\![f]\!]_{\mathcal{C}}$, and thus also to $[\![f]\!]_{\mathcal{C}} \circ \Omega$.

Theorem. Any T-definable function $\mathbb{2}^{\mathbb{N}} \to \mathbb{N}$ is uniformly continuous.

Proof. By the Yoneda Lemma, $[\![f]\!]_{\mathcal{C}} \circ \Omega$ is a probe on $\mathbb{N}$, that is, a uniformly continuous map. Because pointwise equality preserves continuity, $[\![f]\!]$ is also uniformly continuous.

C-Spaces Can Do More!

The development of C-spaces is constructive. Thus we can extract a program to compute moduli of uniform continuity of T-definable functions.

There is a C-continuous map that interprets the fan functional

$$\mathrm{fan} : (\mathsf{Bool}^{\mathsf{Nat}} \to \mathsf{Nat}) \to \mathsf{Nat}$$

which computes the least moduli of uniform continuity.

C-spaces also form a model of Martin-Löf type theory without universe.

Continuity via Syntactic Translation

Idea:

$$\begin{tikzcd}
f = [\![t]\!] & \sim & [\![t^T]\!] & \Longrightarrow & f \text{ is continuous} \\
t \arrow[u, mapsto] \arrow[rr, mapsto] & & t^T \in T \arrow[u, mapsto] & &
\end{tikzcd}$$

- Translate term t into another term t^T.
- Relate the standard interpretations of the term and its translation with some logical relation $[\![t]\!] \sim [\![t^T]\!]$ by induction on t.
- Derive continuity of $[\![t]\!]$ from the proof of $[\![t]\!] \sim [\![t^T]\!]$.
  Derive a term from t^T that internalizes the modulus of continuity.

One Translation of System T

We want to translate Nat to pairs of terms of type $(\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat}$, where the second term is a modulus of continuity of the first term[5].

For convenience, we extend System T with products $(\times, \mathrm{pair}, \mathrm{pr}_1, \mathrm{pr}_2)$.

For each finite type ρ we associate inductively a new one ρ^{b} as

$$\begin{aligned} \mathsf{Nat}^{\mathrm{b}} &:= ((\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat}) \times ((\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat}) \\ (\sigma \to \tau)^{\mathrm{b}} &:= \sigma^{\mathrm{b}} \to \tau^{\mathrm{b}}. \end{aligned}$$

We write $w \equiv \langle \mathrm{V}_w ; \mathrm{M}_w \rangle$ for $w : \mathsf{Nat}^{\mathrm{b}}$ and define $(t : \rho) \mapsto (t^{\mathrm{b}} : \rho^{\mathrm{b}})$ by

$$\begin{aligned} (x)^{\mathrm{b}} &:= x^{\mathrm{b}} & 0^{\mathrm{b}} &:= \langle \lambda\alpha.0 \,;\, \lambda\alpha.0 \rangle \\ (\lambda x.u)^{\mathrm{b}} &:= \lambda x^{\mathrm{b}}.u^{\mathrm{b}} & \mathrm{succ}^{\mathrm{b}} &:= \lambda x.\langle \mathrm{succ} \circ \mathrm{V}_x \,;\, \mathrm{M}_x \rangle \\ (fa)^{\mathrm{b}} &:= f^{\mathrm{b}} a^{\mathrm{b}} & \mathrm{rec}^{\mathrm{b}} &:= ??? \end{aligned}$$

[5] Chuangjie Xu. A syntactic approach to continuity of T-definable functionals. LMCS, 16(1): 22:1–22:11, 2020.

Translate Primitive Recursors

The translation $\mathrm{rec}^{\mathrm{b}} : \rho^{\mathrm{b}} \to (\mathsf{Nat}^{\mathrm{b}} \to \rho^{\mathrm{b}} \to \rho^{\mathrm{b}}) \to \mathsf{Nat}^{\mathrm{b}} \to \rho^{\mathrm{b}}$ has to preserve the computational rules of rec, i.e.,

$$\mathrm{rec}^{\mathrm{b}}(a)(f)(0^{\mathrm{b}}) = a \qquad \mathrm{rec}^{\mathrm{b}}(a)(f)(\mathrm{succ}\ n)^{\mathrm{b}} = f(n^{\mathrm{b}})(\mathrm{rec}^{\mathrm{b}}(a)(f)(n^{\mathrm{b}})).$$

A candidate for $\mathrm{rec}^{\mathrm{b}}(a)(f)$ is $\mathrm{rec}(a)(\lambda k.f(\langle \lambda\alpha.k\,;\lambda\alpha.0\rangle)) : \mathsf{Nat} \to \rho^{\mathrm{b}}$.

We can extend $g : \mathsf{Nat} \to \rho^{\mathrm{b}}$ to $g^* : \mathsf{Nat}^{\mathrm{b}} \to \rho^{\mathrm{b}}$ such that $\forall i.\ g^*(i^{\mathrm{b}}) = g(i)$ by induction on ρ – the Kleisli extension

$$\mathrm{ke}^{\mathsf{Nat}} := \lambda g^{\mathsf{Nat}\to\mathsf{Nat}^{\mathrm{b}}} w^{\mathsf{Nat}^{\mathrm{b}}}.\langle \lambda\alpha.\mathrm{V}_{g(\mathrm{V}_w\alpha)}\alpha\,;\lambda\alpha.\max(\mathrm{M}_{g(\mathrm{V}_w\alpha)}\alpha,\mathrm{M}_w\alpha)\rangle$$

$$\mathrm{ke}^{\sigma\to\tau} := \lambda g^{\mathsf{Nat}\to\sigma^{\mathrm{b}}\to\tau^{\mathrm{b}}} w^{\mathsf{Nat}^{\mathrm{b}}} x^{\sigma^{\mathrm{b}}}.\mathrm{ke}^{\tau}(\lambda k^{\mathsf{Nat}}.g(k,x),w).$$

Hence, we define

$$\mathrm{rec}^{\mathrm{b}} := \lambda af.\mathrm{ke}(\mathrm{rec}(a)(\lambda k.f(\langle\lambda\alpha.k\,;\lambda\alpha.0\rangle))).$$

Continuity via the Translation

We define the following parameterized logical relation $\mathrm{R}^\alpha_\rho \subseteq [\![\rho]\!] \times [\![\rho^{\mathrm{b}}]\!]$ for a given $\alpha : \mathbb{N}^\mathbb{N}$ by induction on ρ

$$n \ \mathrm{R}^\alpha_{\mathsf{Nat}} \ (f, M) \ := \ f\alpha = n \wedge \forall(\beta : \mathbb{N}^\mathbb{N}).(\alpha =_{M\alpha} \beta \to f\alpha = f\beta)$$

$$g \ \mathrm{R}^\alpha_{\sigma\to\tau} \ h \ := \ \forall x^{[\![\sigma]\!]} y^{[\![\sigma^{\mathrm{b}}]\!]} \, (x \ \mathrm{R}^\alpha_\sigma \ y \to gx \ \mathrm{R}^\alpha_\tau \ hy) \, .$$

Lemma. For any term $t : \rho$ in T, we have $[\![t]\!] \ \mathrm{R}^\alpha_\rho \ [\![t^{\mathrm{b}}]\!]$ for any $\alpha : \mathbb{N}^\mathbb{N}$.

We define a term $\Omega : \mathsf{Nat}^{\mathrm{b}} \to \mathsf{Nat}^{\mathrm{b}}$ internalizing the generic sequence by

$$\Omega := \lambda w^{\mathsf{Nat}^{\mathrm{b}}}.\langle \lambda\alpha.\alpha(\mathrm{V}_w\alpha) \, ; \lambda\alpha.\max(\mathrm{V}_w\alpha + 1, \mathrm{M}_w\alpha)\rangle.$$

Theorem. All T-definable function $\mathbb{N}^\mathbb{N} \to \mathbb{N}$ has a T-definable modulus of continuity.

Proof. For any $\alpha : \mathbb{N}^\mathbb{N}$, we have $\alpha \ \mathrm{R}^\alpha_{\mathsf{Nat}\to\mathsf{Nat}} \ [\![\Omega]\!]$ and thus $[\![f]\!]\alpha \ \mathrm{R}^\alpha_{\mathsf{Nat}} \ [\![f^{\mathrm{b}}\Omega]\!]$, i.e., $[\![\mathrm{M}_{f^{\mathrm{b}}\Omega}]\!]$ is a modulus of continuity of $[\![f]\!]$ for all term $f : (\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat}$.

The Translation is Gentzen Style!

Write $J(\rho) \equiv ((\mathsf{Nat} \to \mathsf{Nat}) \to \rho) \times ((\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat})$.

The translation of types of T (extended with products and sums) becomes

$$\mathsf{Nat}^{\mathrm{b}} := J(\mathsf{Nat}) \qquad (\sigma \to \tau)^{\mathrm{b}} := \sigma^{\mathrm{b}} \to \tau^{\mathrm{b}}$$
$$(\sigma + \tau)^{\mathrm{b}} := J(\sigma^{\mathrm{b}} + \tau^{\mathrm{b}}) \qquad (\sigma \times \tau)^{\mathrm{b}} := \sigma^{\mathrm{b}} \times \tau^{\mathrm{b}}$$

It's in the style of Gentzen's negative translation!

$$P^{\mathrm{G}} := \neg\neg P \qquad (\phi \to \psi)^{\mathrm{G}} := \phi^{\mathrm{G}} \to \psi^{\mathrm{G}}$$
$$(\phi \vee \psi)^{\mathrm{G}} := \neg\neg(\phi^{\mathrm{G}} \vee \psi^{\mathrm{G}}) \qquad (\phi \wedge \psi)^{\mathrm{G}} := \phi^{\mathrm{G}} \wedge \psi^{\mathrm{G}}$$
$$(\exists x.\phi)^{\mathrm{G}} := \neg\neg(\exists x.\phi^{\mathrm{G}}) \qquad (\forall x.\phi)^{\mathrm{G}} := \forall x.\phi^{\mathrm{G}}$$

The soundness theorem says $\mathrm{CL} \vdash \phi \iff \mathrm{ML} \vdash \phi^{\mathrm{G}}$.

A Generalization of Gentzen's Negative Translation

Gentzen's Translation can be generalized[6,7,8] by replacing $\neg\neg$ by a nucleus, that is, an endofunction j on formulas such that the followings are provable

$$\phi \to j\phi \qquad (\phi \to j\psi) \to j\phi \to j\psi \qquad (j\phi)[t/x] \leftrightarrow j(\phi[t/x])$$

The translation becomes

$$\begin{aligned} P_j^{\mathrm{G}} &:= jP & (\phi \to \psi)_j^{\mathrm{G}} &:= \phi_j^{\mathrm{G}} \to \psi_j^{\mathrm{G}} \\ (\phi \vee \psi)_j^{\mathrm{G}} &:= j(\phi_j^{\mathrm{G}} \vee \psi_j^{\mathrm{G}}) & (\phi \wedge \psi)_j^{\mathrm{G}} &:= \phi_j^{\mathrm{G}} \wedge \psi_j^{\mathrm{G}} \\ (\exists x.\phi)_j^{\mathrm{G}} &:= j(\exists x.\phi_j^{\mathrm{G}}) & (\forall x.\phi)_j^{\mathrm{G}} &:= \forall x.\phi_j^{\mathrm{G}} \end{aligned}$$

Working with different nuclei, we have

- if $j\phi = \neg\neg\phi$, then $\mathrm{CL} \vdash \phi \implies \mathrm{ML} \vdash \phi_j^{\mathrm{G}}$;
- if $j\phi = (\phi \to X) \to X$, then $\mathrm{CL} \vdash \phi \implies \mathrm{IL} \vdash \phi_j^{\mathrm{G}}$;
- if $j\phi = \phi \vee \bot$, then $\mathrm{IL} \vdash \phi \implies \mathrm{ML} \vdash \phi_j^{\mathrm{G}}$.

[6] Hajime Ishihara. A Note on the Gödel–Gentzen Translation. MLQ, 46(1):135–137, 2000.
[7] Martń Escardó and Paulo Oliva. The Peirce translation. APAL, 163(6):681–692, 2012.
[8] Benno van den Berg. A Kuroda-style j-translation. AML, 58(5-6):627–634, 2019.

A Gentzen-Style Translation of System T

We generalize the translation of T (without sum type for simplicity).

A nucleus $(\mathsf{JNat}, \eta, \kappa)$ consists of a type JNat and two T terms

$$\eta : \mathsf{Nat} \to \mathsf{JNat} \qquad \kappa : (\mathsf{Nat} \to \mathsf{JNat}) \to \mathsf{JNat} \to \mathsf{JNat}.$$

Given $(\mathsf{JNat}, \eta, \kappa)$, we translate types $\sigma \mapsto \sigma^{\mathrm{J}}$ by

$$\mathsf{Nat}^{\mathrm{J}} := \mathsf{JNat} \qquad (\sigma \to \tau)^{\mathrm{J}} := \sigma^{\mathrm{J}} \to \tau^{\mathrm{J}} \qquad (\sigma \times \tau)^{\mathrm{J}} := \sigma^{\mathrm{J}} \times \tau^{\mathrm{J}}$$

and terms $(t : \sigma) \mapsto (t^{\mathrm{J}} : \sigma^{\mathrm{J}})$ by

$$\begin{array}{rclcrclcrcl}
0^{\mathrm{J}} & := & \eta(0) & \quad & (x)^{\mathrm{J}} & := & x^{\mathrm{J}} & \quad & \mathrm{pair}^{\mathrm{J}} & := & \mathrm{pair} \\
\mathrm{succ}^{\mathrm{J}} & := & \kappa(\eta \circ \mathrm{succ}) & & (\lambda x.t)^{\mathrm{J}} & := & \lambda x^{\mathrm{J}}.t^{\mathrm{J}} & & \mathrm{pr}_i & := & \mathrm{pr}_i \\
\mathrm{rec}^{\mathrm{J}} & := & \lambda a f.\mathrm{ke}(\mathrm{rec}(a, f \circ \eta)) & & (tu)^{\mathrm{J}} & := & t^{\mathrm{J}} u^{\mathrm{J}} & & & &
\end{array}$$

Kleisli Extension

Given $a : \rho^{\mathrm{J}}$ and $f : \mathsf{JNat} \to \rho^{J} \to \rho^{\mathrm{J}}$, define $\mathrm{rec}^{\mathrm{J}}(a, f) : \mathsf{JNat} \to \rho^{\mathrm{J}}$.

To extend $\mathrm{rec}(a, f \circ \eta) : \mathsf{Nat} \to \rho^{\mathrm{J}}$,

we cannot directly use $\kappa : (\mathsf{Nat} \to \mathsf{JNat}) \to \mathsf{JNat} \to \mathsf{JNat}$.

We define a term $\mathrm{ke}_\rho : (\mathsf{Nat} \to \rho^{\mathrm{J}}) \to \mathsf{JNat} \to \rho^{\mathrm{J}}$ of the Kleisli extension by induction on ρ as follows

$$\begin{aligned}
\mathrm{ke}_{\mathsf{Nat}}(f, a) &:= \kappa(f, a) \\
\mathrm{ke}_{\sigma\to\tau}(f, a) &:= \lambda x^{\sigma^{\mathrm{J}}}.\mathrm{ke}_\tau(\lambda n. f(n, x), a) \\
\mathrm{ke}_{\sigma\times\tau}(f, a) &:= \langle \mathrm{ke}_\sigma(\mathrm{pr}_1 \circ f, a)\,;\mathrm{ke}_\tau(\mathrm{pr}_2 \circ f, a)\rangle.
\end{aligned}$$

and then use it to define $\mathrm{rec}^{\mathrm{J}}$.

Fundamental Theorem of Logical Relation

Given $\mathrm{R}_{\mathsf{Nat}} \subseteq \mathbb{N} \times [\![\mathsf{JNat}]\!]$, we extend it a logical relation $\mathrm{R}_\rho \subseteq [\![\rho]\!] \times [\![\rho^{\mathrm{J}}]\!]$ for any type ρ in T inductively by

$$f \ \mathrm{R}_{\sigma\to\tau} \ g :\equiv \forall x^{[\![\sigma]\!]} a^{[\![\sigma^{\mathrm{J}}]\!]} \left(x \ \mathrm{R}_\sigma \ a \to fx \ \mathrm{R}_\tau \ ga\right)$$

$$u \ \mathrm{R}_{\sigma\times\tau} \ v :\equiv (u_1 \ \mathrm{R}_\sigma \ v_1) \wedge (u_2 \ \mathrm{R}_\tau \ v_2)$$

Fundamental theorem of logical relation:

For any closed term $t : \rho$ in System T, we have

$$[\![t]\!] \ \mathrm{R}_\rho \ [\![t^{\mathrm{J}}]\!]$$

if $\mathrm{R}_{\mathsf{Nat}}$ satisfies

$\forall n (n \ \mathrm{R}_{\mathsf{Nat}} \ [\![\eta]\!] n)$ and $\forall f^{\mathbb{N}\to\mathbb{N}} g^{\mathbb{N}\to[\![\mathsf{JNat}]\!]} \left(\forall i (fi \ \mathrm{R}_{\mathsf{Nat}} \ gi) \to f \ \mathrm{R}_{\mathsf{Nat}\to\mathsf{Nat}} \ [\![\kappa]\!] g\right).$

Example: Continuity of Functions $\mathbb{N}^{\mathbb{N}} \to \mathbb{N}$

Continuity nucleus $\mathsf{JNat} = (\mathsf{Nat}^{\mathsf{Nat}} \to \mathsf{Nat}) \times (\mathsf{Nat}^{\mathsf{Nat}} \to \mathsf{Nat})$ with

$$\eta := \lambda n^{\mathsf{Nat}}.\langle \lambda\alpha.n\,;\lambda\alpha.0\rangle$$

$$\kappa := \lambda g^{\mathsf{Nat}\to\mathsf{JNat}} w^{\mathsf{JNat}}.\langle \lambda\alpha.\mathrm{V}_{g(\mathrm{V}_w\alpha)}\alpha\,;\lambda\alpha.\max(\mathrm{M}_{g(\mathrm{V}_w\alpha)}\alpha, \mathrm{M}_x\alpha)\rangle$$

Generic sequence $\Omega : \mathsf{JNat} \to \mathsf{JNat}$ defined by

$$\Omega := \kappa(\lambda n^{\mathsf{Nat}}.\langle \lambda\alpha.\alpha n\,;\lambda\alpha.n+1\rangle)$$

Continuity relation $\mathrm{R}^{\alpha}_{\mathsf{Nat}} \subseteq \mathbb{N} \times [\![\mathsf{JNat}]\!]$ defined by

$$n\ \mathrm{R}^{\alpha}_{\mathsf{Nat}}\ (f, M)\ :=\ f\alpha = n \wedge \forall(\beta : \mathbb{N}^{\mathbb{N}}).(\alpha =_{M\alpha} \beta \to f\alpha = f\beta)$$

Show that $\mathrm{R}^{\alpha}_{\mathsf{Nat}}$ satisfies

$$\forall n(n\ \mathrm{R}^{\alpha}_{\mathsf{Nat}}\ [\![\eta]\!]n) \quad \text{and} \quad \forall f^{\mathbb{N}\to\mathbb{N}} g^{\mathbb{N}\to[\![\mathsf{JNat}]\!]}\,(\forall i(fi\ \mathrm{R}^{\alpha}_{\mathsf{Nat}}\ gi) \to f\ \mathrm{R}^{\alpha}_{\mathsf{Nat}\to\mathsf{Nat}}\ [\![\kappa]\!]g)\,.$$

Example: Uniform Continuity of Functions $\mathbb{N}^{\mathbb{N}} \to \mathbb{N}$

We say a map $M : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ is a modulus of uniform continuity of $f : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ if

$$\forall(\gamma : \mathbb{N}^{\mathbb{N}})(\alpha, \beta \le \gamma).\,(\alpha =_{M\gamma} \beta \to f\alpha = f\beta)$$

where $\alpha \le \gamma :\equiv \forall i.\alpha_i \le \gamma_i$.

Theorem. All T-definable function $\mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ has a T-definable modulus of uniform continuity.

Uniform-continuity nucleus $\mathsf{JNat} = (\mathsf{Nat}^{\mathsf{Nat}} \to \mathsf{Nat}) \times (\mathsf{Nat}^{\mathsf{Nat}} \to \mathsf{Nat})$ with

$$\eta := \lambda n^{\mathsf{Nat}}.\langle \lambda\alpha.n\,;\lambda\alpha.0\rangle$$
$$\kappa := \lambda g^{\mathsf{Nat}\to\mathsf{JNat}} w^{\mathsf{JNat}}.\langle \lambda\alpha.\mathrm{V}_{g(\mathrm{V}_w\alpha)}\alpha\,;\lambda\alpha.\max(\ldots,\ldots)^{9}\rangle$$

Uniform-continuity relation $\mathrm{R}^{\alpha}_{\mathsf{Nat}} \subseteq \mathbb{N} \times [\![\mathsf{JNat}]\!]$ defined by

$$n\ \mathrm{R}^{\alpha}_{\mathsf{Nat}}\ (f, M)\ :=\ f\alpha = n \wedge \forall(\beta, \gamma \le \alpha).(\beta =_{M\alpha} \gamma \to f\beta = f\gamma).$$

[9] Agda dev.: `https://cj-xu.github.io/agda/GentzenTrans/UniformContinuity.html`

Example: Majorizability (bounds of programs)[10]

Define a relation $\mathrm{maj}_\rho \subseteq [\![\rho]\!] \times [\![\rho]\!]$ by

$$n \; \mathrm{maj}_{\mathsf{Nat}} \; m \;:=\; n \leq m$$
$$f \; \mathrm{maj}_{\sigma\to\tau} \; g \;:=\; \forall x^{[\![\sigma]\!]} y^{[\![\sigma]\!]} \left(x \; \mathrm{maj}_\sigma \; y \to fx \; \mathrm{maj}_\tau \; gy\right).$$

We say t is majorized by u if $t \; \mathrm{maj} \; u$, and call u a majorant of t.

Consider the nucleus

$$\mathsf{JNat} := \mathsf{Nat} \qquad \eta(n) := n \qquad \begin{cases} \kappa(g,0) := g(0) \\ \kappa(g,n+1) := \max(\kappa(g,n), g(n+1)). \end{cases}$$

The idea is that JNat is the type of majorants of some numbers.

Theorem. For any $t : \rho$ of T, we have $[\![t]\!] \; \mathrm{maj}_\rho \; [\![t^{\mathrm{J}}]\!]$.

Proof. (1) $n \leq [\![\eta]\!] n = n$. (2) $fi \leq gi \leq [\![\kappa]\!](g,j)$ for any $i \leq j$.

[10] W. A. Howard. Hereditarily majorizable functionals of finite type. In *Metamathematical Investigation of Intuitionistic Arithmetic and Analysis*, pp. 454–461. Springer, Berlin, 1973.

More Examples

Study specific higher-order objects, e.g. continuity of type 2 functionals

More applications: totally, number of evaluation steps, closure under bar recursion[11,12], continuation passing style transformation[13], trace property analysis[14], runtime monitoring (?), ...

[11] Helmut Schwichtenberg. On bar recursion of types 0 and 1. JSL, 44(3):325–329, 1979.
[12] Paulo Oliva and Silvia Steila. A direct proof of Schwichtenberg's bar recursion closure theorem. JSL, 83(1):70–83, 2018.
[13] Gilles Barthe and Tarmo Uustalu. CPS translating inductive and coinductive types. PEPM'02.
[14] Ulrich Schöpp and Chuangjie Xu. A generic type system for featherweight Java. FTfJP'21.

Other Negative Translations

Kolmogorov: $\phi \mapsto \phi^{\mathrm{Ko}}$

$$P^{\mathrm{Ko}} := \neg\neg P \qquad (\phi \to \psi)^{\mathrm{Ko}} := \neg\neg(\phi^{\mathrm{Ko}} \to \psi^{\mathrm{Ko}})$$
$$(\phi \vee \psi)^{\mathrm{Ko}} := \neg\neg(\phi^{\mathrm{Ko}} \vee \psi^{\mathrm{Ko}}) \qquad (\phi \wedge \psi)^{\mathrm{Ko}} := \neg\neg(\phi^{\mathrm{Ko}} \wedge \psi^{\mathrm{Ko}})$$
$$(\exists x.\phi)^{\mathrm{Ko}} := \neg\neg(\exists x.\phi^{\mathrm{Ko}}) \qquad (\forall x.\phi)^{\mathrm{Ko}} := \neg\neg(\forall x.\phi^{\mathrm{Ko}})$$

Kuroda (modified[15]): $\phi \mapsto \neg\neg\phi^{\mathrm{Ku}}$

$$P^{\mathrm{Ku}} := P \qquad (\phi \to \psi)^{\mathrm{Ku}} := \phi^{\mathrm{Ku}} \to \neg\neg\psi^{\mathrm{Ku}}$$
$$(\phi \vee \psi)^{\mathrm{Ku}} := \phi^{\mathrm{Ku}} \vee \psi^{\mathrm{Ku}} \qquad (\phi \wedge \psi)^{\mathrm{Ku}} := \phi^{\mathrm{Ku}} \wedge \psi^{\mathrm{Ku}}$$
$$(\exists x.\phi)^{\mathrm{Ku}} := \exists x.\phi^{\mathrm{Ku}} \qquad (\forall x.\phi)^{\mathrm{Ku}} := \forall x.\neg\neg\phi^{\mathrm{Ku}}$$

Theorem. $\mathrm{CL} \vdash \phi \iff \mathrm{ML} \vdash \phi^{\mathrm{Ko}} \iff \mathrm{ML} \vdash \neg\neg\phi^{\mathrm{Ku}}$

[15] Paulo Oliva and Gilda Ferreira. On the relation between various negative translations. In *Logic, Construction, Computation*, vol. 3 of Mathematical Logic Series, pp. 227–258, 2012.

A Kuroda-style Translation of System T

We need the general notion of nucleus $(\mathrm{J}, \eta, \kappa)$ where

- J is an endofunction on types of T
- $\eta : \tau \to \mathrm{J}\tau$
- $\kappa : (\sigma \to \mathrm{J}\tau) \to \mathrm{J}\sigma \to \mathrm{J}\tau$

Each type ρ of T is translated to a type $\mathrm{J}[\rho]$ where $[\rho]$ is defined by

$$[\mathsf{Nat}] := \mathsf{Nat} \qquad [\sigma \to \tau] := [\sigma] \to \mathrm{J}[\tau].$$

And each term $t : \rho$ is translated to a term $[t] : \mathrm{J}[\rho]$ as follows

$$\begin{aligned} [x] &:= \eta(\bar{x}) & [0] &:= \eta(0) \\ [\lambda x.t] &:= \eta(\lambda \bar{x}.[t]) & [\mathrm{succ}] &:= \eta(\eta \circ \mathrm{succ}) \\ [fa] &:= [f] \bullet [a] & [\mathrm{rec}] &:= \eta(\lambda a.\eta(\lambda f.\eta(\mathrm{rec}(\eta a, \lambda n x. f n \bullet x)))) \end{aligned}$$

where $f \bullet a : \mathrm{J}\tau$ for $f : \mathrm{J}(\sigma \to \mathrm{J}\tau)$ and $a : \mathrm{J}\sigma$ is defined by

$$f \bullet a := \kappa(\lambda g^{\sigma \to \mathrm{J}\tau}.\kappa(g, a), f).$$

Continuity via The Kuroda-style Translation

We can use our continuity nucleus, but here we recover the stateful approach of Coquand and Jaber[16] and Powell[17] and Cohen and Rahli[18], with no extension to System T.

State monad: $\rho \mapsto (S \to \rho \times S)$

Continuity state nucleus: $(\mathrm{J}, \eta, \kappa)$ defined by

$$\begin{aligned} \mathrm{J}(\rho) &:= \mathsf{Nat} \to (\mathsf{Nat} \to \mathsf{Nat}) \to \rho \times \mathsf{Nat} \\ \eta(x^\rho) &:= \lambda m\alpha.\langle x\,;m\rangle \\ \kappa(g^{\sigma\to\mathrm{J}\tau}, w^{\mathrm{J}\sigma}) &:= \lambda m\alpha.\langle (g(wm\alpha)_1 m\alpha)_1\,;\max((g(wm\alpha)_1 m\alpha)_2, (wm\alpha)_2, m)\rangle \end{aligned}$$

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[16] Thierry Coquand and Guilhem Jaber. A computational interpretation of forcing in type theory. In *Epistemology versus Ontology*, vol. 27, pp. 203–213. Springer Netherlands, 2012.
[17] Thomas Powell. A functional interpretation with state. LICS'18.
[18] Liron Cohen and Vincent Rahli. Realizing Continuity Using Stateful Computations. 2022

Continuity via The Kuroda-Style Translation (cont.)

Continuity state nucleus: $(\mathrm{J}, \eta, \kappa)$ defined by

$$\begin{aligned} \mathrm{J}(\rho) &:= \mathsf{Nat} \to (\mathsf{Nat} \to \mathsf{Nat}) \to \rho \times \mathsf{Nat} \\ \eta(x^{\rho}) &:= \lambda m\alpha.\langle x\,;m\rangle \\ \kappa(g^{\sigma\to\mathrm{J}\tau}, w^{\mathrm{J}\sigma}) &:= \lambda m\alpha.\langle (g(wm\alpha)_1 m\alpha)_1\,;\max((g(wm\alpha)_1 m\alpha)_2, (wm\alpha)_2, m)\rangle \end{aligned}$$

Generic sequence $\Omega : \mathrm{J}(\mathsf{Nat} \to \mathrm{J}\mathsf{Nat})$ defined by

$$\Omega := \eta(\lambda n^{\mathsf{Nat}} m^{\mathsf{Nat}} \alpha^{\mathsf{Nat}\to\mathsf{Nat}}.\langle \alpha n\,;\max(n+1, m)\rangle)$$

Theorem. For any closed T term $f : (\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat}$, the map $[\![\mathrm{pr}_2 \circ (([f] \bullet \Omega)0)]\!] : \mathbb{N}^{\mathbb{N}} \to \mathbb{N}$ is a modulus of continuity of $[\![f]\!]$.

Gentzen-Style vs Kuroda-Style

The Gentzen-style translation is call-ba-name.

The Kuroda-style translation is call-ba-value.

Example: Consider $\lambda\alpha.\mathrm{rec}(\alpha_{10}, \lambda xy.0, 1)$.

- Using the Gentzen-style translation, the modulus is $\lambda\alpha.0$.
- Using the Kuroda-style translation, the modulus is $\lambda\alpha.11$.

Summary

We have looked at some approaches to computing moduli of continuity:

- Effectful – directly reflect the idea of the algorithm
- Semantic – intuitive thanks to the selected structure
- Syntactic – easily generalized for other purposes

Thank you!