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A coinductive approach to digital computation

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Outline

- Introduction
- Induction and coinduction
- Digit spaces
- Metric digit spaces
- Program extraction
- Case studies
- Conclusion

The aims of this talk

- to outline a constructive theory of digital computation;
- to show that program extraction from proofs is a practical method for obtaining certified programs for digital computation.

Background

- Exact Real Arithmetic via infinite streams of Signed Digits and Linear Fractional Transformations
- Coalgebraic modelling of infinite data types
- Proof Theory: Program extraction from proofs via realisability
- Domain-theoretic modelling and termination proofs

Example: computing with signed digits

$\mathbb{I} := [-1, 1] \subseteq \mathbb{R}$
$\mathrm{SD} := \{-1, 0, 1\}$
$x \in \mathbb{I}$
$a = (a_n)_{n \in \mathbb{N}} \in \mathrm{SD}^\omega$

$$x \sim a \quad :\Leftrightarrow \quad x = \sum_{n=0}^{\infty} a_n \cdot 2^{-(n+1)}$$

A function $f : \mathbb{I} \to \mathbb{I}$ is *represented* by a function $\hat{f} : \mathrm{SD}^\omega \to \mathrm{SD}^\omega$ if

$$\forall x, a \, (\, x \sim a \Rightarrow f(x) \sim \hat{f}(a) \,)$$

Power series as infinite composition

$$\sum_{n=0}^{\infty} a_n \cdot 2^{-(n+1)} = \frac{1}{2}(a_0 + \frac{1}{2}(a_1 + \ldots))$$

$\mathrm{av}_d : \mathbb{I} \to \mathbb{I}, \quad \mathrm{av}_d(x) := \frac{1}{2}(d + x) \quad (d \in \mathrm{SD}).$

$$\sum_{n=0}^{\infty} a_n \cdot 2^{-(n+1)} = \mathrm{av}_{a_0}(\mathrm{av}_{a_1}(\ldots)) = \mathrm{av}_{a_0} \circ \mathrm{av}_{a_1} \circ \ldots$$

Therefore, $x \sim a \;\Leftrightarrow\; x = \mathrm{av}_{a_0} \circ \mathrm{av}_{a_1} \circ \ldots$.

$\mathrm{AV} := \{\mathrm{av}_{-1}, \mathrm{av}_0, \mathrm{av}_1\} \subseteq \mathbb{I} \to \mathbb{I}.$

$(\mathbb{I}, \mathrm{AV})$ is an example of a *digit space*.

Digit spaces

We study digit spaces (X, D), where X is a set and $D \subseteq X \to X$, and characterise the functions $f : X \to Y$ that have a continuous digital representation $\hat{f} : D^\omega \to E^\omega$.

The characterisation does not refer to infinite objects (like streams of digits), but uses a combined inductive/coinductive definition.

Program extraction yields implementations of $\hat{f}$ by finitely branching non-wellfounded trees.

We also consider *metric digit spaces* (X, σ, P, D), where σ is a metric on X and $P \subseteq X$ is dense, and study the relation between digital representability and uniform continuity.

Induction

$\Phi \colon \mathcal{P}(U) \to \mathcal{P}(U)$ is monotone if $X \subseteq Y$ implies $\Phi(X) \subseteq \Phi(Y)$.

A set $X \subseteq U$ is Φ-*closed* if $\Phi(X) \subseteq X$.

$\mu\Phi$, the set *inductively* defined by Φ, is the least Φ-closed set.

Closure	$\Phi(\mu\Phi) \subseteq \mu\Phi$
Induction	if $\Phi(X) \subseteq X$, then $\mu\Phi \subseteq X$

Coinduction

A set $X \subseteq U$ is Φ-*coclosed* if $X \subseteq \Phi(X)$.

$\nu\Phi$, the set *coinductively* defined by Φ, is the largest Φ-coclosed set.

Coclosure	$\nu\Phi \subseteq \Phi(\nu\Phi)$
Coinduction	if $X \subseteq \Phi(X)$, then $X \subseteq \nu\Phi$

Digital maps (motivation)

Let $x = \mathrm{av}_{a_0} \circ \mathrm{av}_{a_1} \circ \dots$. Consider $h\colon \mathbb{I} \to \mathbb{I}$ (e.g. a polynomial)

Writing a digit

$$\begin{aligned} h(x) &= h \circ \mathrm{av}_{a_0} \circ \mathrm{av}_{a_1} \circ \dots \\ &= \mathrm{av}_b \circ ((\mathrm{av}_b^{-1} \circ h) \circ \mathrm{av}_{a_0} \circ \mathrm{av}_{a_1} \circ \dots) \qquad \text{if } h[\mathbb{I}] \subseteq \mathrm{av}_b[\mathbb{I}] \end{aligned}$$

Reading a digit

$$\begin{aligned} h(x) &= h \circ \mathrm{av}_{a_0} \circ \mathrm{av}_{a_1} \circ \dots \\ &= (h \circ \mathrm{av}_{a_0}) \circ \mathrm{av}_{a_1} \circ \dots \end{aligned}$$

After reading finitely many digits writing must be possible again.

Digital maps (definition)

Let (X, D) and (Y, E) be digit spaces.
We define the set $\mathrm{C}_{D,E} \subseteq X \to Y$ of *digital maps* as follows.

Let F, G range over subsets of $X \to Y$
and let $\nu F. \dots$ stand for $\nu\lambda F \dots$ e.t.c.

$\mathrm{C}_{D,E} :=$

$$\nu F. \mu G. \{e \circ f \mid e \in E, f \in F\} \cup \{h : X \to Y \mid \forall d \in D\, h \circ d \in G\}$$

Identity and composition

Identity Lemma

Let (X, D) be a digit spaces.

(a) $\mathrm{id}_X \in \mathrm{C}_{D,D}$.

(b) $D \subseteq \mathrm{C}_{D,D}$.

Composition Lemma

Let (X_i, D_i) (i=1,2,3) be digit spaces.

If $f \in \mathrm{C}_{D_1,D_2}$ and $g \in \mathrm{C}_{D_2,D_3}$, then $g \circ f \in \mathrm{C}_{D_1,D_3}$.

The category of digit spaces

By the Identity Lemma and the Composition Lemma, digit spaces and digital maps form a category.

Product Lemma

The category $\mathcal{D}$ has finite products.

Digital global elements

The set of global elements of a digit space (X, D) is

$$\mathrm{C}_D := \mathrm{C}_{\mathbf{1},(X,D)}$$

where $\mathbf{1}$ denotes the terminal object $(\mathbf{1}, \{\mathrm{id}_\mathbf{1}\})$ in $\mathcal{D}$. We identify C_D with a subset of X.

Global Element Lemma

$$\mathrm{C}_D = \nu A.\{d(x) \mid d \in D, x \in A\} \quad \overset{\text{roughly}}{=} \{d_0 \circ d_1 \circ \dots \mid (d_n)_{n \in \mathbb{N}} \in D^\omega\}$$

Application Lemma

If $f \in \mathrm{C}_{D,E}$ and $x \in \mathrm{C}_D$, then $f(x) \in \mathrm{C}_E$.

Proof: Composition Lemma.

Metric spaces

A *metric space* $X = (X, \sigma, P)$ consists of

- a set X,
- a metric σ on X,
- a dense set $P \subseteq X$ (of *concrete* elements).

For a rational number $\epsilon > 0$ and $p \in P$ we define

$$\mathrm{B}_\epsilon(p) := \{x \in X \mid \sigma(p, x) \leq \epsilon\}$$

For convenience, we only work with metric spaces that are *bounded*, i.e. $X \subseteq \mathrm{B}_M(p)$ for some $M > 0$ and $p \in P$.

Uniform continuity

Let $X = (X, P, \sigma)$ and $Y = (Y, Q, \tau)$ be metric spaces.

In the following: $p \in P$, $q \in Q$, $a, b \in \mathbb{R}^+$, $\delta, \epsilon \in \mathbb{Q}^+$,
$\hat{a} := \{\delta \in \mathbb{Q}^+ \mid \delta \leq a\} =]0, a]$.

A *modulus* is a relation $m \subseteq \mathbb{Q}^+ \times \mathbb{Q}^+$ such that

$$\forall b \, \exists a \;\; m[\hat{a}] \subseteq \hat{b}$$

A relation $f \subseteq X \times Y$ is *m-continuous*, if

$$\forall \delta, p \, \exists \epsilon \in m(\delta) \, \exists q \;\; f[\mathrm{B}_\delta(p)] \subseteq \mathrm{B}_\epsilon(q)$$

A relation f is *uniformly continuous (u.c.)* if it is m-continuous for some modulus m.

Properties of uniform continuity

Lemma

A relation $f \subseteq X \times Y$ is u.c. iff it is a partial function which is uniformly continuous on its domain,
$\mathrm{dom}(f) := \{x \in X \mid \exists y \in Y\,(x, y) \in f\}$, in the usual sense, i.e.

$$\forall \epsilon\, \exists \delta\, \forall x, x' \in \mathrm{dom}(F)$$

$$\sigma(x, x') \leq \delta \Rightarrow \tau(f(x), f(x')) \leq \epsilon$$

Composition Lemma

If $g \subseteq Y \times Z$ and $f \subseteq X \times Y$ are uniformly continuous, so is $g \circ f \subseteq X \times Z$.

Lipschitz conditions and contractivity

For $\lambda \geq 0$ we define

$$m_\lambda := \{(\delta, \epsilon) \mid \epsilon \leq \lambda\delta\}$$

Clearly, m_λ is a modulus and $m_\lambda \circ m_\gamma = m_{\lambda\gamma}$.

A relation $f \subseteq X \times Y$ is called *Lipschitz* if it is m_λ-continuous for some $\lambda \geq 0$. If $\lambda < 1$, we call f *contracting*.

Lemma A relation $f \subseteq X \times Y$ is λ-continuous iff it is a partial function and $\tau(f(x), f(x')) \leq \lambda \cdot \sigma(x, x')$ for all $x, x' \in \mathrm{dom}(f)$. Hence a function is Lipschitz iff it is Lipschitz in the usual sense.

Metric digit spaces

A *metric digit space* $X = (X, \sigma, P, D)$ is a metric space (X, σ, P) together with a set of digits $D \subseteq X \to X$.

(X, σ, P, D) is called

- *contracting* if there is $\lambda < 1$ such that all $d \in D$ are contracting with factor λ.
- *invertible* if d^{-1} is u.c. for all $d \in D$.
- *covering* if there is an $\epsilon_0 > 0$ such that, for all $\epsilon > 0$ and $p \in P$, either there exists $d \in D$ with $\mathrm{B}_\epsilon(p) \subseteq d[X]$, or $\epsilon > \epsilon_0$.
- *finitely covering* if there is a finite subset of D which is uniformly covering.

Example: $(\mathbb{I}, \mathrm{AV})$ has all these properties.

Characterisation of uniform continuity

Characterisation Lemma

Let $X = (X, \sigma, P, D)$ and $Y = (Y, \tau, Q, E)$ be metric digit spaces.
Set $\mathrm{U} := \{f : X \to Y \mid f \text{ u.c.}\}$ and $\mathrm{C} := \mathrm{C}_{D,E}$.

(a) If X is contracting, and Y is invertible and covering, then $\mathrm{U} \subseteq \mathrm{C}$.

(b) Assume D is finite. If X is invertible and finitely covering, and Y is contracting, then $\mathrm{C} \subseteq \mathrm{U}$.

Corollary (change of digits)

Let (X, σ, P) be a metric space and let $D, E \subseteq X \to X$. If D is contracting, and E is invertible and covering, then $\mathrm{C}_D \subseteq \mathrm{C}_E$.

Proof

The identity function on X is u.c. and hence in $\mathrm{C}_{D,E}$, by (a).

The type of a formula

To every formula A we assign the type $\tau(A)$ of its *realisers*, i.e. the type a program extracted from a proof of A will have:

- $\tau(A)$ is the unit type if A contains neither $\vee$ nor predicate variables (A may contain predicate constants like "$=$", "$\leq$" and "$\in \mathbb{R}$").
- The propositional connectives $\wedge$, $\vee$, $\Rightarrow$ are translated into the type constructors $\times$, $+$, $\to$.
- Quantifiers and terms are ignored.
- Predicate variables are translated into type variables.
- Inductive and coinductive definitions are translated into initial algebras and terminal coalgebras, respectively.

Example: τ("f is uniformly continuous")

Recall that $f : \mathbb{I} \to \mathbb{I}$ is uniformly continuous if there is some modulus m such that

$$\forall \delta, p \, \exists \epsilon \in m(\delta) \, \exists q \;\; f[\mathrm{B}_\delta(p)] \subseteq \mathrm{B}_\epsilon(q)$$

Since $\delta, \epsilon, p, q \in \mathbb{Q}$ and $\tau(\epsilon \in \mathbb{Q}) = \mathbb{Q}$, and furthermore $\tau(\epsilon \in m(\delta))$ is the unit type, we have

$$\tau(f \text{ u.c}) = \mathbb{Q} \times \mathbb{Q} \to \mathbb{Q} \times \mathbb{Q}$$

Example: $\tau(\mathrm{C}_{\mathrm{AV}})$

Recall the definition of $\mathrm{C}_{\mathrm{AV}} \subseteq \mathbb{I}$:

$$\begin{aligned}
\mathrm{C}_{\mathrm{AV}} &= \nu A\,.\,\{d(x) \in \mathbb{I} \mid d \in \mathrm{AV}, x \in A\} \\
&= \nu A\,.\,\{y \in \mathbb{R} \mid -1 \leq y \leq 1 \wedge \\
&\qquad\qquad \exists d, x\,(d \in \mathrm{AV} \wedge x \in A \wedge y = \mathrm{av}_a(x))\}
\end{aligned}$$

where

$\mathrm{AV} = \{\mathrm{av}_a \mid a \in \mathrm{SD}\} = \{d : \mathbb{R} \to \mathbb{R} \mid \exists a \in \mathrm{SD}\, d = \mathrm{av}_a\}$

$\mathrm{SD} = \{-1, 0, 1\} = \{a \mid a = -1 \vee a = 0 \vee a = 1\}$:

Therefore

$$\begin{aligned}
\tau(\mathrm{C}_{\mathrm{AV}}) &= \nu\alpha\,.\,\mathrm{SD} \times \alpha \\
&= \mathrm{SD}^{\omega}
\end{aligned}$$

Example: $\tau(\mathrm{C}_{\mathrm{AV},\mathrm{AV}})$

Recall the definition of $\mathrm{C}_{\mathrm{AV},\mathrm{AV}} \subseteq \mathbb{I} \to \mathbb{I}$:

$$
\begin{aligned}
\mathrm{C}_{\mathrm{AV},\mathrm{AV}} &= \nu F \,.\, \mu G \,. \\
&\quad \{e \circ f : \mathbb{I} \to \mathbb{I} \mid e \in \mathrm{AV}, f \in F\} \cup \\
&\quad \{h : \mathbb{I} \to \mathbb{I} \mid \forall d \in \mathrm{AV}\ h \circ \mathrm{av}_d \in G\} \\
&= \nu F \,.\, \mu G \,. \\
&\quad \{h : \mathbb{R} \to \mathbb{R} \mid h[\mathbb{I}] \subseteq \mathbb{I} \wedge \\
&\qquad (\exists e, f\,(e \in \mathrm{AV} \wedge f \in F \wedge h = e \circ f) \vee \\
&\qquad (h \circ d_{-1} \in G \wedge h \circ d_0 \in G \wedge h \circ d_1 \in G))\}
\end{aligned}
$$

Therefore

$$
\tau(\mathrm{C}_{\mathrm{AV},\mathrm{AV}}) \quad = \quad \nu\alpha \,.\, \mu\beta \,.\, \mathrm{SD} \times \alpha + \beta^3
$$

See also [Hancock, Pattinson, Ghani]

Understanding $\tau(\mathrm{C}_{\mathrm{AV},\mathrm{AV}}) \;=\; \nu\alpha\,.\,\mu\beta\,.\,\mathrm{SD} \times \alpha + \beta^3$

Define T as the largest solution of the domain equation

$$T = \mathrm{SD} \times T + T^3$$

i.e. the elements of T are non-wellfounded trees with two kinds of nodes:

- **Writing nodes:** $W(d, t)$ where $d \in \mathrm{SD}$ and $t \in T$.
- **Reading nodes:** $R(t_{-1}, t_0, t_1)$ where $t_i \in T$.

$\tau(\mathrm{C}_{\mathrm{AV},\mathrm{AV}})$ is the set of those trees in T that have on every infinite path infinitely many writing nodes.

Realising inductive definitions

Assume the set operator Φ corresponds to the type operator φ.

Then, the inductively defined set $\mu\Phi$ together with the axioms

Closure	$\Phi(\mu\Phi) \subseteq \mu\Phi$
Induction	if $\Phi(X) \subseteq X$, then $\mu\Phi \subseteq X$

are realised by the initial algebra $(\mu\varphi, \mathrm{In}_\varphi)$
and the family It_φ of universal arrows, i.e.

$$\begin{aligned} \mathrm{In}_\varphi &: \varphi(\mu\varphi) \to \mu\varphi \\ \mathrm{It}_\varphi[s] &: \mu\varphi \to \alpha \quad (s : \varphi(\alpha) \to \alpha) \end{aligned}$$

with the defining recursion equation expressing that $\mathrm{It}_\varphi[s]$ is an algebra morphism

$$\mathrm{It}_\varphi[s] \circ \mathrm{In}_\varphi = s \circ \mathbf{map}_\varphi(\mathrm{It}_\varphi[s])$$

Hence, the function $\mathrm{It}_\varphi[s]$ is defind by *structural recursion* with step function s.

Realising coinductive definitions

For coinductive definitions the situation is dual.

The coinductively defined set $\nu\Phi$ and its axioms

Coclosure $\quad \nu\Phi \subseteq \Phi(\nu\Phi)$

Coinduction $\quad$ if $X \subseteq \Phi(X)$, then $X \subseteq \nu\Phi$

are realised by the terminal coalgebra $(\nu\varphi, \mathrm{Out}_\varphi)$
and the family $\mathrm{Coit}_\varphi[s]$ of universal arrows

$$\begin{array}{lcl} \mathrm{Out}_\varphi & : & \nu\varphi \to \varphi(\nu\varphi) \\ \mathrm{Coit}_\varphi[s] & : & \alpha \to \nu\varphi \quad (s : \alpha \to \varphi(\alpha)) \end{array}$$

with the equation expressing that $\mathrm{Coit}_\varphi[s]$ is a coalgebra morphism

$$\mathrm{Out}_\varphi \circ \mathrm{Coit}_\varphi[s] = \mathbf{map}_\varphi(\mathrm{Coit}_\varphi[s]) \circ s$$

Hence $\mathrm{Coit}_\varphi[s]$ is the function defined by *guarded recursion* with "state transition" function s.

Iterated maps

The family of logistic maps (transformed from $[0,1]$ to $\mathbb{I} = [-1,1]$):

$$f_a : \mathbb{I} \to \mathbb{I}, \quad f(x) = a * (1 - x^2) - 1 \qquad (0 \leq a \leq 2).$$

f_a is $2a$-Lipschitz, hence uniformly continuous (Lipschitz Lemma), hence in $\mathrm{C} := \mathrm{C}_{\mathrm{AV},\mathrm{AV}} \subseteq \mathbb{I} \to \mathbb{I}$ (Characterisation Lemma (a)).

Hence the iterated maps f_a^n are in C (Composition Lemma) and therefore define signed digit stream transformers (Application Lemma).

The main point of this example is to demonstrate the **memoizing effect** of the tree representation of u.c. functions (see also Hinze, Altenkirch).

$f_2(x) = 2 * (1 - x^2) - 1$. Computing $f_2^n(1/3)$

```
n = 1
Exact SD:        PPZZPZZNZZPZZNZZPZZNZZPZZNZZPZZNZZPZZNZZPZZNZZPZZNZZP
                 ZZNZZPZ
... as Float:    0.7777777777777778
Float:           0.7777777777777778
E. R. as Float:  0.7777777777777778
Exact Rat:       7%9
```

```
n = 5
Exact SD:        ZZPZZZZNZNPNPZZPZZPNZZPNNPNPNZPZZZZPZZPZZNPNZPZNPZZP
                 NZZNPZZN
... as Float:    0.12049965049830123
Float:           0.120499650498301
E. R. as Float:  0.12049965049830123
Exact Rat:       223288285122943%1853020188851841
```

$f_2(x) = 2 * (1 - x^2) - 1$. Computing $f_2^n(1/3)$

```
n = 10
Exact SD:       PPZZZZZZZNZPZPNZPNZZNPPNPZNZNPZNPNZZZPZZNZZZZZZNPZZZ
                PZZZZZZP
... as Float:   0.7493017528354341
Float:          0.7493017528354383
E. R. as Float: 0.7493017528354341
Exact Rat:      27978316675610959552032915495388607472289906338590 21
7774055173255304299733074691954912657704663663159685744782612553100 4
5527546961997331006445654781809039630456092940068836697073821288546 2
6484441799922520206913440208511659717592406730766348908290438792803 8
6558029477655393267909117475098554856434796345789572706247161825034 3
9978777944335158852343126604645010342393641602472732771231105614576 7
8032965340804314088653106584085030272795940439991187397499259127202 0
988019085255733835241249955 83%37339184874102004353295975418486658822
5409776783734007750636931722079040617265251229993688938803977220468 7
6506543147515810872705459216085858135133698280918731419174859426258 0
9388070199519564042855718180410466812887974029255176680123406172983 9
6574731619152386723046235125934896058590588284654793540505936202376 5
4780744273058214452705898875625145281779341335214192074462302751872 9
18543286237573706398548531947641692626381997288700690701389925652429
```

$f_2(x) = 2 * (1 - x^2) - 1$. Computing $f_2^n(1/3)$

```
n = 30
Exact SD:       PZZZZZPNPZPNPPNPNPZZZZZNZPNZZZZZZPNPZPNPNPNPZZNPZNZP
                ZNZPZZZN
... as Float:   0.5062674954994535
Float:          0.5062674897488822


n = 60
Exact SD:       NNNZPNPZZNZNPZPNZPNZZPZZNZZNPZZPNPZPNZNZPZZNZNZZNZZP
                NZNZZZZN
... as Float:   -0.8526437597407311
Float:          -0.9469915748606237


n = 600
Exact SD:       NNZZZNPZZNZZZZZNPNZPZZPNPPNPNZZNPZZZPNZZZNZPNPZNPZNZ
                ZZZNPZNZ
... as Float:   -0.7587994543102519
Float:          0.33218504745590244
```

π

For the metric digit space $(\mathbb{I}, \mathrm{AV})$ we have $\pi/4 \in \mathrm{C}_D$.

Proof We use the formula

$$\frac{\pi}{4} = \frac{1}{2} + \frac{1}{3}\left(\frac{1}{2} + \frac{2}{5}\left(\frac{1}{2} + \frac{3}{7}\left(\frac{1}{2} + \frac{4}{9}\left(\frac{1}{2} + \dots\right)\right)\right)\right)$$

i.e. $\pi/4 = f_0(f_1(\dots))$ where

$$f_n(x) := \frac{1}{2} + \frac{n\,x}{2n+1}.$$

Hence we have $\pi/4 \in \mathrm{C}_F$ where $F := \{f_n \mid n \in \mathbb{N}\}$. Since F is contracting and AV is invertible and covering, it follows, by the Change of Digits L., $\pi/4 \in \mathrm{C}_D$.

Integration

For a continuous function $f : \mathbb{I} \to \mathbb{R}$ we set
$\int f := \int_{-1}^{1} f = \int_{-1}^{1} f(t)\,\mathrm{d}t \in \mathbb{R}$.

Lemma

(a) $\int(\mathrm{av}_i \circ f) = \mathrm{av}_{2\cdot i}(\int f)$
(b) $\int f = \frac{1}{2}(\int(f \circ \mathrm{av}_{-1}) + \int(f \circ \mathrm{av}_1))$.

(see also Simpson, Scriven)

Integration Lemma

Let (X, σ, P, D) be a covering and invertible metric digit system and $f \in \mathrm{C}_{D\otimes\mathrm{AV},\mathrm{AV}}$. Then the function mapping $(a, b, x) \in \mathbb{I}^2 \times X$ to $\int_a^b f(x, t)\,\mathrm{d}t$ is well-defined and uniformly continuous.

Conclusion

- “Proofs as programs” deserves a “last chance”.
- New (correct!) programs extracted that would have been difficult to “guess”.
- Using a fine tuning of realisability it is possible to do abstract mathematics as usual, and still get computational content.

Further work

- Clarify connections with related work by Edalat, Heckmann, Potts, Escardo, Simpson, Bauer, Taylor, Hutchinson, Scriven, Hancock, Pattinson, Buchholz, Bertot, Niqui, O'Connor, Spitters, ...
- Implement and automate (joint work with the Munich logic group (Minlog) and Anton Setzer (Agda)).
- Overcome limitations: no finite system of contracting and uniformly covering digits exists on the compact metric space of non-empty compact sets with the Hausdorff metric (joint work with Dieter Spreen).
- Power series via higher type digits.
- "Realiser sensitive" logic:
  $\forall x\,(A(x) \to B(x) \to C(x))$ vs.
  $\forall x\,(A(x) \to \neg B(x) \lor C(x))$ for decidable $B(x)$.

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