EXPLICIT MODAL LOGICS

of single-conclusion proof systems

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2007

Formal proof theory T – a theory in which the human arguments about proofs and provability should be formalized.

Requirements:

- encodings for formulas, proofs and programs
- $Provable(x)$ – "x is provable"
- $Proof(x, y)$ – "x is a proof of y"

Suitable candidates: $T = PA, ZF, \ldots$

But all of them are VERY UNFRIENDLY in this role: axioms and rules say nothing about proofs and provability.

Improvements – proof theoretical interfaces for T:

$Provable$ — modal provability logics (**GL/S4**)
$Proof$ — logics of proofs (**FPL/LP**)

Verification of decision procedures.

$$Decide(\ulcorner\varphi\urcorner) \begin{array}{l} \nearrow \text{ yes } (\varphi \text{ is valid}) \\ \searrow \text{ fail} \end{array}$$

"Private" verification (for oneself):

establish $\quad Decide(\ulcorner\varphi\urcorner) = \text{yes} \Rightarrow Provable(\ulcorner\varphi\urcorner).$

"Public" verification:

construct $\boxed{t}$ s.t. $\quad Decide(\ulcorner\varphi\urcorner) = \text{yes} \Rightarrow Proof(t, \ulcorner\varphi\urcorner),$

$$\boxed{\text{distribute } t + \text{trusted } ProofChecker().}$$

Core proof logic language:

$$\left.\begin{array}{l} p_0, p_1, \ldots \text{ – proof variables} \\ !^1, \times^2 \text{ – operations on proofs} \end{array}\right\} \longmapsto \mathbf{Tm}$$

$$\left.\begin{array}{l} S_0, S_1, \ldots \text{ – sentence variables} \\ \neg, \vee, \wedge, \rightarrow, (\_ : \_) \end{array}\right\} \longmapsto \mathbf{Fm}$$

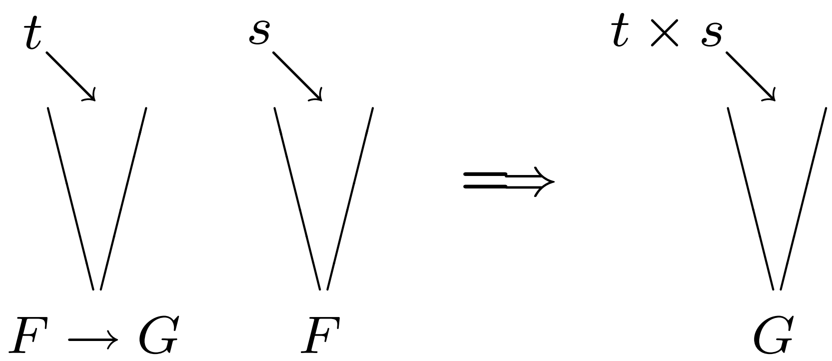
$$\frac{t \in \mathbf{Tm}, \quad F \in \mathbf{Fm}}{(t : F) \in \mathbf{Fm}}$$

Informal semantics:

$t : F$ – the arithmetical statement "t proves F",

$\times, !$ – act on proof codes:

$\times$



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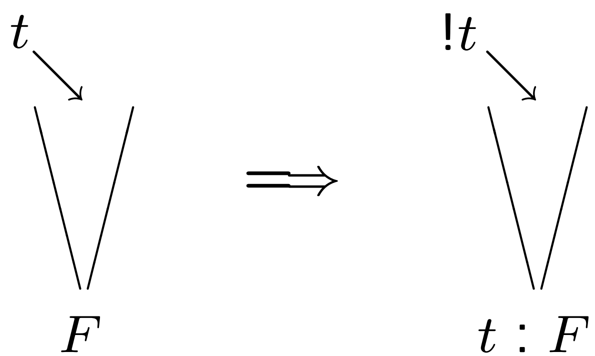

Single-valued proof predicates – reflect the external derivations:

"x is a code of a derivation and
y is the code of its last formula"

$\boxed{p{:}F \wedge p{:}G \Rightarrow F = G \qquad \text{How to formalize this without "=" ?}}$

$$t_1{:}F_1 \wedge \ldots \wedge t_n{:}F_n \ \longmapsto\ S{:=}\{\, t_i = t_j \Rightarrow F_i = F_j \mid 1 \leq i,j \leq n \,\}$$

Def: A unifier σ of S is a substitution s.t. $t_i\sigma \not\equiv t_j\sigma$ or $F_i\sigma \equiv F_j\sigma$ holds for every i, j.

Def: $A = B\,(mod\,S)$ iff $A\sigma \equiv B\sigma$ for every unifier σ of S.

Lemma: *The relation* $A = B\,(mod\,S)$ *is decidable.*

Unification axioms:

$$t_1{:}F_1 \wedge \ldots \wedge t_n{:}F_n \rightarrow (A \leftrightarrow B) \text{ when } A = B\,(mod\,S).$$

System **FLP** (Single-conclusion proof logic)

A0. Propositional axioms and rules

A1. $t\!:\!(F \to G) \to (s\!:\!F \to ts\!:\!G)$

A2. $t\!:\!F \to F$

A3. $t\!:\!F \to !t\!:\!(t\!:\!F)$

A4. Unification axioms

Theorem 1: **FLP** is sound and complete w.r. to arithmetical provability interpretations based on single-valued proof predicates.

Theorem 2: **FLP** is decidable.

Theorem 3: The rule with a scheme $\dfrac{F_1,\ldots,F_n}{F}$ is **PA**-admissible iff **FLP**$\vdash F_1 \wedge \ldots \wedge F_n \to F$.
Moreover, all the operations on **PA**-derivations induced by admissible rules of this kind can be represented by proof terms (Lifting Lemma).

Language extension by references

Ex: $\texttt{goal}(t)$ such that $\quad t : F \;\Rightarrow\; \texttt{goal}(t) = F \qquad \forall t, F$

Axiom scheme: $\boxed{t : F \rightarrow t : \texttt{goal}(t)}$

NB: $\texttt{goal}$ cannot be a constant function symbol here:

$(A \wedge B)$ and $\texttt{goal}(t)$ must be unifiable, otherwise

$t\!:\!(A \wedge B),\ t\!:\!\texttt{goal}(t) \vdash \bot$ (from Unification axiom).

So, $\vdash \neg t\!:\!(A \wedge B)$. The same with $\neg, \vee, \rightarrow, :$.

$\boxed{\texttt{goal()} \text{ is SO variable, or reference}}$

We use more powerful unification algorithm that can deal with SO variables. The set of all Unification axioms is still decidable.

Example with pattern matching:

$\texttt{refl}(t)$ such that $\quad t:(s:F) \Rightarrow \texttt{refl}(t)=s \qquad \forall t,s,F$

Axiom scheme: $\boxed{t:\underbrace{(s:F)}_{\varphi(s)} \rightarrow t:(\texttt{refl}(t):F)}$

Here $\varphi(x)$ is a pattern, x is a metavariable.

$t \longmapsto G := \texttt{goal}(t) \longmapsto \texttt{match } G \texttt{ with } \varphi(x); \texttt{return } x.$

General case:

$\texttt{f}(t)$ such that $\quad t:\varphi(\ldots,Y,\ldots) \Rightarrow \texttt{f}(t)=Y;$

$\varphi = F_0 \wedge p_1 : F_1 \wedge \ldots \wedge p_n : F_n$ where $F_i = F_i(p_1,\ldots,p_n;S_1,\ldots,S_m)$.

System $\mathbf{FLP}_{ref}$ $= \mathbf{FLP} +$ (all references)

The scope of Unification axioms (*A4*) now includes references. The semantics of $A = B\,(mod\,S)$ relation involves Second Order unification, but in restricted form which still remains decidable.

Theorems 1',2',3'. $\mathbf{FLP}_{ref}$ *is decidable, sound and complete w.r. to arithmetical single-conclusion proof interpretations. It provides the same admissibility test for arithmetical inference rules specified by schemes in* $\mathbf{FLP}_{ref}$*-language.*

Ex:

$\texttt{is\_proof}(t) := t : \texttt{goal}(t)$ means "t is a complete proof";

$\exists\bar{x}_{t:\varphi(\bar{x})}\, F(\bar{x}) := t : \varphi(\bar{\mathrm{g}}(t)) \wedge F(\bar{\mathrm{g}}(t))$;
$\forall\bar{x}_{t:\varphi(\bar{x})}\, F(\bar{x}) := t : \varphi(\bar{\mathrm{g}}(t)) \rightarrow F(\bar{\mathrm{g}}(t))$.

$$\frac{\texttt{is\_proof}(p)}{\texttt{goal}(p)} \qquad \frac{\texttt{is\_proof}(p)}{\texttt{refl}(!p) : \texttt{goal}(p)} \qquad \frac{p : \neg\texttt{goal}(p)}{\perp}$$

$$\frac{\exists S_0, S_{1\,p_0:(S_0 \rightarrow S_1)}\, p_1 : S_0}{\texttt{is\_proof}(p_0 p_1)}$$

Reflexive combinatory logic

$\mathbf{RCL}_{\rightarrow}$ (Artemov, 2003), extends $\mathbf{CL}_{\rightarrow}$ (Curry).

$$!t, \quad t \cdot s, \quad t\!:\!F, \quad F \rightarrow G$$

Rigid typing: x_i^F (typed proof variables);

$\mathbf{k}^{(\dots)}$ $\mathbf{s}^{(\dots)}$, $\mathbf{d}^{(\dots)}$, $\mathbf{o}^{(\dots)}$, $\mathbf{c}^{(\dots)}$ (typed proof constants).

Inductive definitions for two judgements:

- "F is well formed formula"
- "$\Gamma \vdash F$"

$\boxed{\text{For every } t \text{ there is at most one } F \text{ s.t. } t\!:\!F \text{ is well formed.}}$

$\mathbf{RCL}_{\rightarrow}$, wf-rules:

Standard wf-rules from $\mathbf{CL}_{\rightarrow}$ for $\rightarrow$, $\cdot$, $\mathbf{k}^{(\ldots)}$, $\mathbf{s}^{(\ldots)}$;

$$\frac{F \textbf{ -wf}}{x_i^F : F \textbf{ -wf}} \qquad \frac{t : F \textbf{ -wf}}{!t : t : F \textbf{ -wf}} \qquad \frac{t : F \textbf{ -wf}}{\mathbf{d}^{\,t:F\rightarrow F} : (t : F \rightarrow F) \textbf{ -wf}}$$

$$\frac{u : (F \rightarrow G),\ v : F \textbf{ -wf}}{\mathbf{o}^{(\ldots)} : (\,u : (F \rightarrow G) \rightarrow (v : F \rightarrow uv : G)\,) \textbf{ -wf}}$$

$$\frac{t : F \textbf{ -wf}}{\mathbf{c}^{(\ldots)} : (\,t : F \rightarrow !t : t : F\,) \textbf{ -wf}}$$

$\boxed{\text{“ } F \textbf{ -wf” is polynomial time decidable. (N. Krupski)}}$

$\mathbf{RCL}_{\rightarrow}$, derivability:

Precondition: all formulas below must be well formed.

Axioms: $t{:}F \rightarrow F$

$\mathbf{k}^{(\ldots)}{:}(F \rightarrow (G \rightarrow F))$

$\mathbf{s}^{(\ldots)}{:}((F \rightarrow (G \rightarrow H)) \rightarrow ((F \rightarrow G) \rightarrow (F \rightarrow H)))$

$\mathbf{d}^{(\ldots)}{:}(t{:}F \rightarrow F)$

$\mathbf{o}^{(\ldots)}{:}(u{:}(F \rightarrow G) \rightarrow (v{:}F \rightarrow uv{:}G))$

$\mathbf{c}^{(\ldots)}{:}(t{:}F \rightarrow !t{:}t{:}F)$

Rule: $F \rightarrow G,\ F \vdash G$.

$\boxed{\text{“}\Gamma \vdash F\text{” is } PSPACE\text{-complete. (N. Krupski)}}$