TableauxRocq: A Deep-Embedding of Free-Variable Tableaux in Rocq

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Once Upon a Time...

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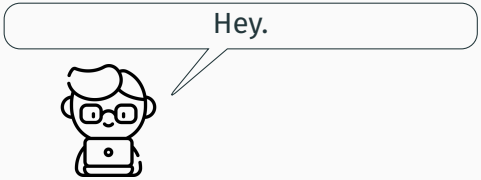

Once Upon a Time...

I've been meaning to mecanize our paper.

Hey.

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Do you know about some library for free-variable tableaux in a proof assistant?

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Hey.

I've also asked around and it doesn't seem like there is one.

I don't.

Hi.

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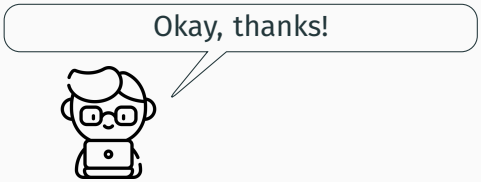

Once Upon a Time...

I'll make one, then.

Okay, thanks!

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It'll be small though, with only have some easy results, like soundness.

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Okay, thanks!

Sure. That's already a good first step.

Once Upon a Time...

It'll be small though, with only have some easy results, like soundness.

I'll make one, then.

Okay, thanks!

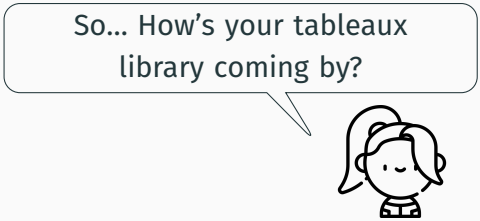
Good luck!

Sure. That's already a good first step.

Once Upon a Time...

Some months later...

Once Upon a Time...

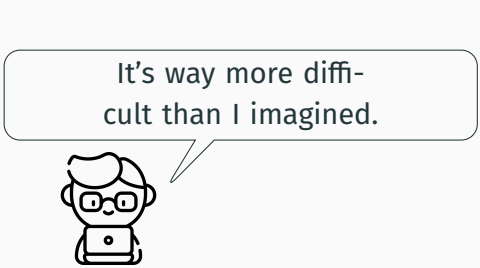


Once Upon a Time...

It's way more difficult than I imagined.

So... How's your tableaux library coming by?

Once Upon a Time...



Once Upon a Time...

Do you have 20 minutes?

It's way more difficult than I imagined.

Oh! Why?

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Sure.

Oh! Why?

So... How's your tableaux library coming by?

Once Upon a Time...

Then let me tell you about it.

Do you have 20 minutes?

It's way more diffi-
cult than I imagined.

Sure.

Oh! Why?

So... How's your tableaux
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FOL, But Not Fool

Small locally nameless syntax:

$$
\begin{array}{llll}
t, t_i & ::= & n \in \mathbb{N} \mid X \in \mathcal{X} \mid f(t_1, \ldots, t_n) & f \in \mathcal{F} \\
F, G & ::= & \bot \mid P(t_1, \ldots, t_n) \mid \neg F \mid F \vee G \mid \forall F & P \in \mathcal{P}
\end{array}
$$

with operations:

- instantiation $F[t]$,
- substitution $F\sigma$, $\sigma = \{X_1 \mapsto t_1, \ldots, X_n \mapsto t_n\}$.

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Free-variable tableaux, *en bref*:

- proofs by contradiction,
- one-sided upside-down sequents,
- placeholder (in $\mathcal{X}$) awaiting term instantiation (given by substitution).

Elementary, Dear Audience

Axioms (i.e., contradictions):

$$\frac{\bot}{\odot}\odot_{\bot} \qquad\qquad \frac{F, \neg G}{\sigma}\odot_{\sigma}, F\sigma = G\sigma$$

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Expansion:

$$\frac{\neg\neg F}{F}\alpha_{\neg\neg} \qquad \frac{\neg(F \vee G)}{\neg F, \neg G}\alpha_{\neg\vee} \qquad \frac{F \vee G}{F \quad G}\beta_{\vee}$$

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Instantiation:

$$\frac{\forall F}{F[X]}\gamma_{\forall} \qquad\qquad \frac{\neg(\forall F)}{\neg F[\mathrm{sko}(X_1, \ldots, X_n)]}\delta_{\neg\forall}$$

Wait, it's All Choice? Always Has Been

$\mathrm{sko}(X_1, \ldots, X_n)$?

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$\mathrm{sko}(X_1, \ldots, X_n)? \to$ "suitable" term. Multiple suitable terms, e.g.:

$$\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\forall\neg(\neg D(0) \vee \forall D(0))}{\neg(\neg D(X) \vee \forall D(0))}\,\gamma_\forall}{\neg\neg D(X), \neg(\forall D(0))}\,\alpha_{\neg\vee}}{D(X), \neg(\forall D(0))}\,\alpha_{\neg\neg}}{\neg D(f(X)), \forall\neg(\neg D(0) \vee \forall D(0))}\,\delta_{\neg\forall}}{\neg(\neg D(Y) \vee \forall D(0))}\,\gamma_\forall}{\neg\neg D(Y), \neg(\forall D(0))}\,\alpha_{\neg\vee}}{D(Y), \neg D(f(X))}\,\alpha_{\neg\neg}}{\{Y \mapsto f(X)\}}\,\odot$$

"Outer" Skolemization

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sko$(X_1, \ldots, X_n)$? $\rightarrow$ "suitable" term. Multiple suitable terms, e.g.:

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"Inner" Skolemization

Is This a Sound Proof System?

Many different Skolemizations. Goals:

- smaller proof-search space so faster automated provers,
- more compact proofs,
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How do we justify these unsound systems?

- Syntactic soundness via translation.[1]
- Semantic soundness via deep embedding (this work).

[1] *A Generic Deskolemization Strategy*, Rosain et al. (LPAR 2024).

Mom, Can We Have a Proof Certificate at Home?

Side-bonus of this approach: nicer proof certificates.

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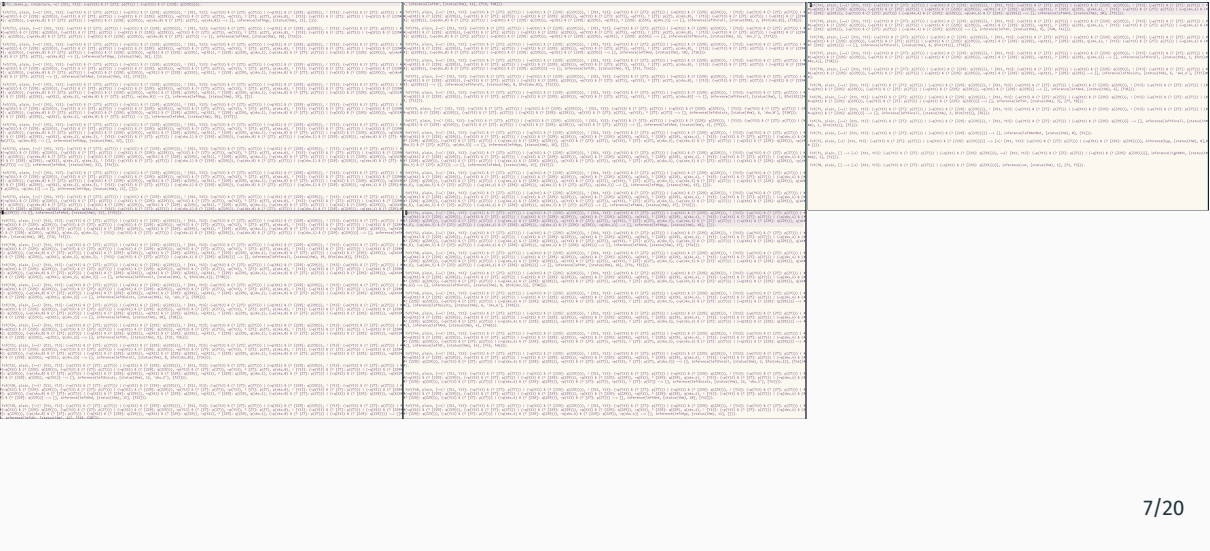
Consider:

$$\dfrac{\dfrac{\dfrac{\forall\forall((\neg P(0) \wedge \exists P(0)) \vee (\neg Q(1) \wedge \exists Q(0)))}{(\neg P(Y) \wedge \exists P(0)) \vee (\neg Q(X) \wedge \exists Q(0))}\,\gamma_\forall \times 2}{\neg P(Y) \wedge \exists P(0)}\,\beta_\vee \qquad \dfrac{\neg Q(X) \wedge \exists Q(0)}{\neg Q(X), \exists Q(0)}\,\alpha_\wedge}{\dfrac{\neg P(Y), \exists P(0)}{P(c), \neg P(Y)}\,\delta_\exists \qquad \dfrac{\neg Q(X), \exists Q(0)}{Q(d), \neg Q(X)}\,\delta_\exists}$$
$$\dfrac{P(c), \neg P(Y)}{\{Y \mapsto c\}}\,\odot \qquad \dfrac{Q(d), \neg Q(X)}{\{X \mapsto d\}}\,\odot$$

Does not look particularly bad. Right...?

(Mom) No, There Is a Proof Certificate at Home:



(Mom) No, There Is a Proof Certificate at Home:

Over 100 lines of 500+ characters proof-steps from a 5-lines proof!!!

You Know, I'm Somewhat of a Proof Certificate Myself

In our system:[1]

```
fof(goal, definition,
    ! [X, Y] : (~p(Y) & (? [Z]: p(Z))) | (~q(X) & (? [Z] : q(Z)))).
fof(desko, negated_conjecture, goal).
fof(s, substitution, { X -> d ; Y -> c }, inner).

fof(s0, plain, goal, inference(forall, [s1], fot(X)).
fof(s1, plain, ! [Y] : (~p(Y) & (? [Z]: p(Z))) | (~q(X) & (? [Z] : q(Z))),
    inference(forall, [s2], fot(Y)).
fof(s2, plain, (~p(Y) & (? [Z]: p(Z))) | (~q(X) & (? [Z] : q(Z))), inference(or, [
    s3, s4])).
fof(s3, plain, ~p(Y) & (? [Z]: p(Z)), inference(and, [s5])).
fof(s5, plain, ? [Z]: p(Z), inference(exists, [s6], fot(c)).
fof(s6, plain, [~p(Y), p(c)], inference(hyp, []).
fof(s4, plain, ~q(X) & (? [Z]: q(Z)), inference(and, [s7])).
fof(s7, plain, ? [Z]: q(Z), inference(exists, [s8], fot(d)).
fof(s8, plain, [~q(X), q(d)], inference(hyp, []).
```

[1] Non-contractual format. Subject to change.

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```

How?

```
fof(s2, plain, (~p(Y) & (? [Z]: p(Z))) | (~q(X) & (? [Z] : q(Z))), inference(or, [
    s3, s4])).
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Trade Offer—I Receive: a Proof, You Receive: Validity

An object $\langle \Gamma, \pi \rangle : \mathsf{Proof}$ is:

- a list of formulas, and
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Predicate $\mathsf{isTableau} : \mathsf{Proof} \to \mathsf{Sub} \to \mathsf{Prop}$, want:

Soundness

For every $\langle \Gamma \blacktriangleright \neg F, \pi \rangle : \mathsf{Proof}$ and $\sigma : \mathsf{Sub}$,

$$\mathsf{isTableau}\ \langle \Gamma \blacktriangleright \neg F, \pi \rangle\ \sigma \implies \Gamma \models F.$$

Here, we work with Tarski's semantics.

Why Is it, When Something Happens, it Is Always You?

Tableaux: one-sided sequents. Usually formalized as inductive predicate.

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Syntactically unsound:

- $M(\Gamma) \wedge M(\neg(F[\mathrm{sko}(X_1, \ldots, X_n)]))$ proves false.
- Want: $M(\Gamma)$ proves false, with $\neg(\forall F) \in \Gamma$. Assume $M(\Gamma)$.
- Show: $M(\Gamma), M(\neg(F[\mathrm{sko}(X_1, \ldots, X_n)]))$.

But $M(\neg(\forall F))$ **does not** entail $M(\neg(F[\mathrm{sko}(X_1, \ldots, X_n)]))$.

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Direct proof fails. Other proof techniques?

You Fool! I Have 70 Alternative Proofs!

What does literature[2,3,4] says?

[2] *First-order Logic and Automated Theorem Proving*, Fitting (1996)
[3] *The Liberalized δ-Rule in Free Variable Semantic Tableaux*, Hähnle and Schmitt (1994)
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But with inductive definition, β rule fails: 2 induction hypotheses.

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Friendship Ended with Inductives. Now Binary Relations Are My Best Friends.

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Tableau proof (T, σ) is:

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Note

Definition is generic w.r.t. any *semantically sound* Skolemization.

Satisfied? How Would You Rate Your Experience?

Lemma

If $T_1 \triangleright T_2$ and T_1 satisfiable, then so is T_2.

Proof.

β rule case: OK — a single induction hypothesis.

δ rule case: needs new model M' w.r.t. selected Skolemization.
Given by "soundness": $M(\neg(\forall F)) \implies M'(\neg F[t])$, t is skolemized term. □

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Soundness follows as T_n is not satisfiable.

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...But having inductive representation would be useful.

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Interesting to maintain inductive specification internally.

- TableauxRocq: built as a library—offers more familiar API.
- More possibilities: can be easier to prove some properties on one version.
- Well-maintained API and tactics for both versions.

No Choice Needed, We Are Better

Implemented an output in TableauxRocq format in Goéland.[5]

[5] *Goéland: A Concurrent Tableau-Based Theorem Prover*, Cailler et al. (IJCAR 2022)

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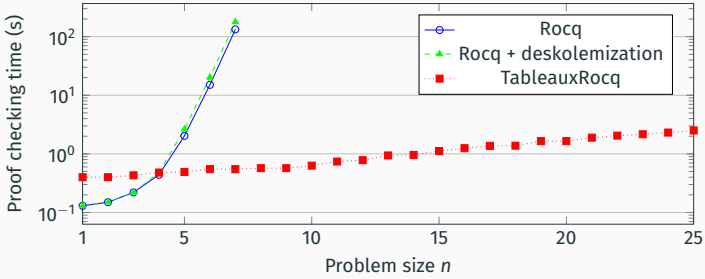

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Real-World Is Overrated, Change my Mind

Experiments (using the TPTP library):

- filter: only first-order problems without equality,
- proof search: list the problems that Goéland passes,
- proof generation: generate syntactic and semantic proof for each problem.

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Results:[2]

Output mode	Skolemization	#problems	Med. time	Avg. time	#faster
Syntactic	Outer	172	0.24s	1.74s	169
TableauxRocq			0.72s	1.91s	3
Syntactic	Inner	177	0.24s	1.70s	173
TableauxRocq			0.71s	1.38s	4

[2] Slightly differ from the ones in the paper as we have rerun them.

0 Days Since Last Lesson Learned

Takeaway of the benches:

Advantages	Inconvenients
Outputing proofs is easy Faster on proofs that use Skolemization Better scaling (faster on bigger proofs)	Slower in the given problem set

0 Days Since Last Lesson Learned

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Instead of running it inside Rocq, extract the checker!

- Even easier to output proof (e.g., format shown in slide 8).
- Faster (binary compiled in OCaml).
- Retains its advantages on Skolemization-heavy/big proofs.

My Mind Has Changed

Same experiments, but with extracted checker:

Output mode	Skolemization	#problems	Med. time	Avg. time	#faster
Syntactic	Outer	172	0.24s	1.74s	0
TableauxRocq			0.72s	1.91s	0
Extracted			0.003s	0.008s	172
Syntactic	Inner	177	0.24s	1.7s	0
TableauxRocq			0.71s	1.38s	0
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Extracted checker is sound and fast!

$\rightarrow$ seems like the best way (to date) to certify ATPs outputs.

Conclusion and Future Work

In this work:

- first formalization of free-variable tableaux and their semantic soundness,
- provide sound proof-checker,
- proof output in Goéland, yielding promising benchs,
- difficulty: find the right definition and provide a good API.

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Near future:

- improve internal API with RocqInterface,[3]
- inductive specification of the algorithm,
- implement equality reasoning,
- prove completeness.

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Available at https://github.com/jrosain/TableauxRocq

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