

Proof Reconstruction in Classical Propositional Logic

(work in progress)

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(joint work with Andrés Sicard-Ramírez)

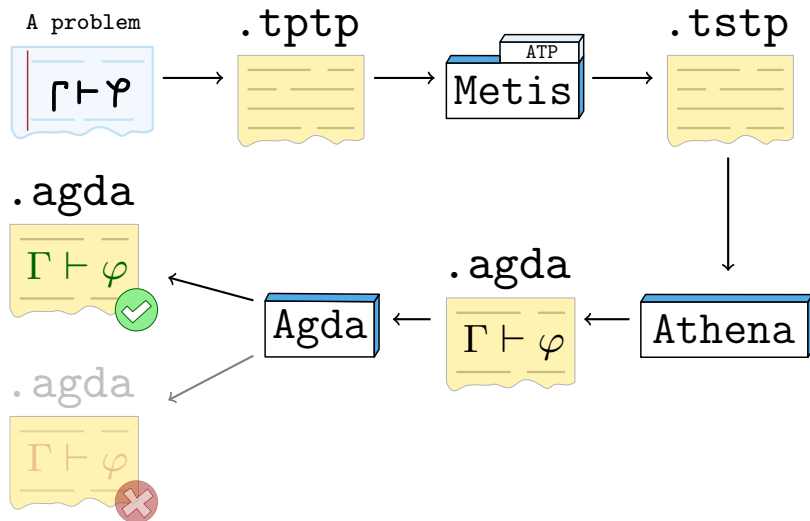
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Universidad EAFIT
Medellín, Colombia

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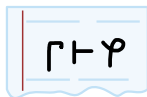
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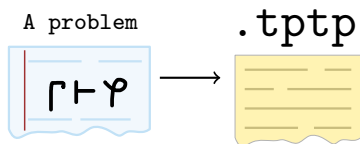


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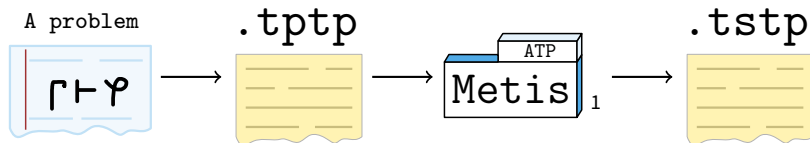
A problem



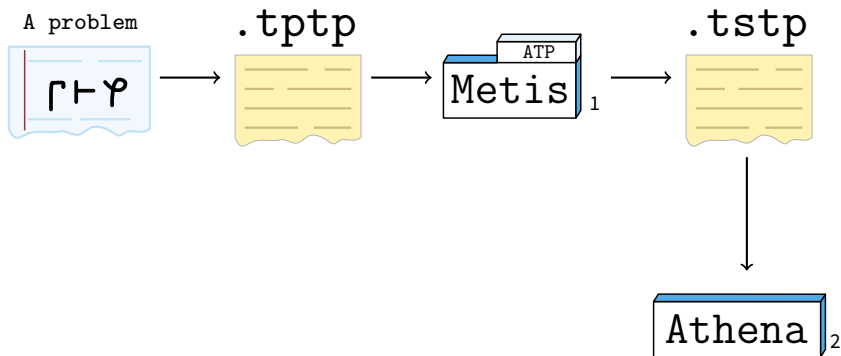




¹<http://www.gilith.com/software/metis>.

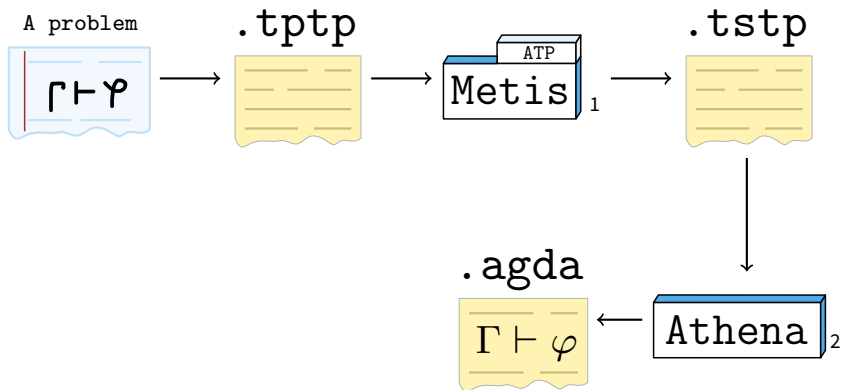


¹<http://www.gilith.com/software/metis>.



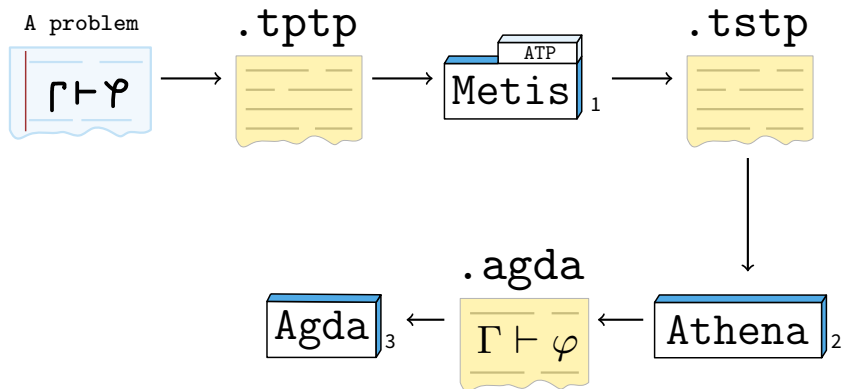
¹<http://www.gilith.com/software/metis>.

²<http://github.com/jonaprieto/athena>.



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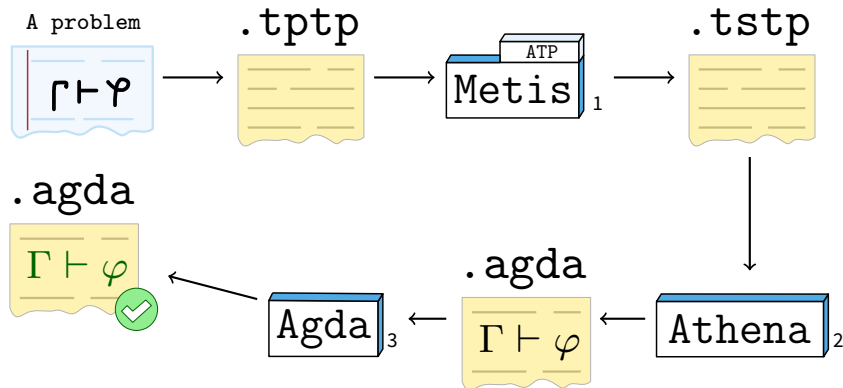
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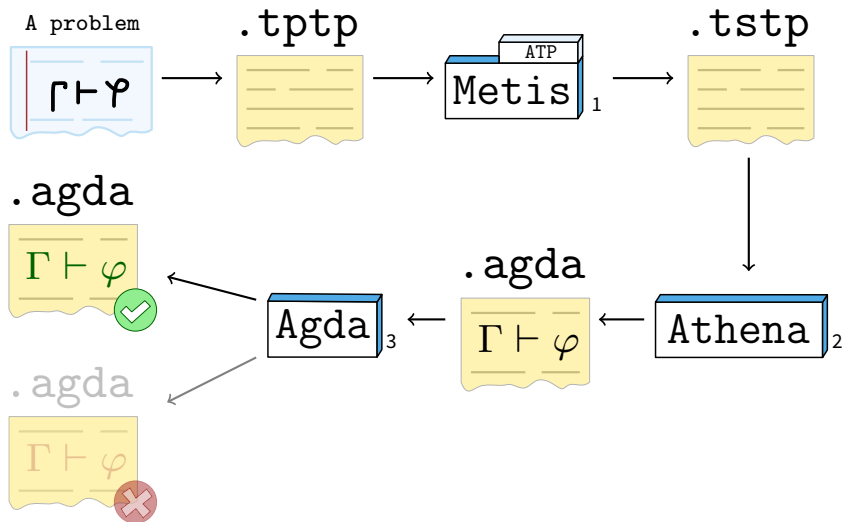
³<http://github.com/agda/agda>.



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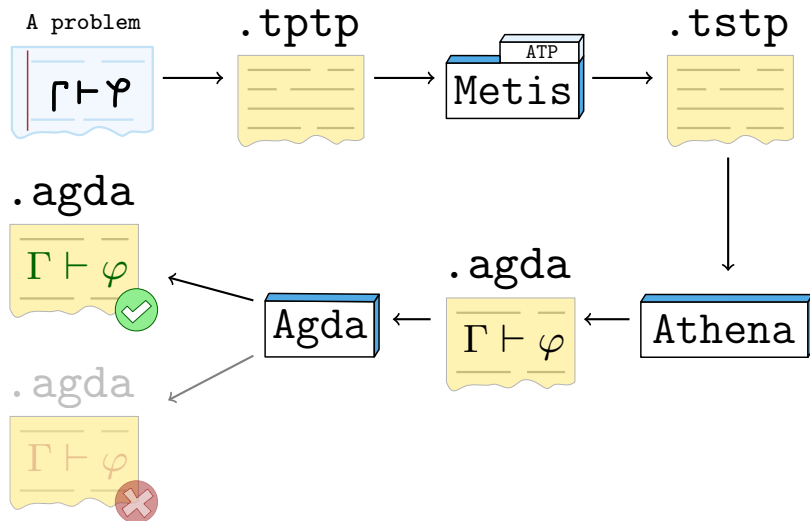


¹<http://www.gilith.com/software/metis>.

²<http://github.com/jonaprieto/athena>.

³<http://github.com/agda/agda>.

- ▶ *Ambiguities*: their output typically omits crucial information, such as which term is affected by rewriting.
- ▶ *Lack of standards*: automatic provers generate different output formats and employ a variety of inference systems
- ▶ *Complexity*: a single automatic prover may use numerous inference rules with complicated behaviors
- ▶ *Problem transformations*: ATPs re-order literals and make other changes to the clauses they are given



.tptp



- ▶ Is a language⁴ to encode problems (Sutcliffe, 2009)
- ▶ Is the input of the ATPs
- ▶ Annotated formulas with the form

```
language(name, role, formula).
```

language FOF or CNF

name to identify the formula within the problem

role axiom, definition, hypothesis, conjecture

formula formula in TPTP format

⁴<http://www.cs.miami.edu/~tptp/TPTP/SyntaxBNF.html>.

► $p \vdash p$

```
fof(myaxiom, axiom, p).  
fof(goal, conjecture, p).
```

► $\vdash \neg(p \wedge \neg p) \vee (q \wedge \neg q)$

```
fof(goal, conjecture, ~ ((p & ~ p) | (q & ~ q))).
```



Metis is an automatic theorem prover for First-Order Logic with Equality (Hurd, 2003)

Why Metis?

- ▶ Open source implemented in Standard ML
- ▶ Each refutation step is one of *six rules*
- ▶ Reads problem in TPTP format
- ▶ Outputs *detailed* proofs in TSTP format

⁵<http://www.gilith.com/software/metis/>.

TSTP derivations by Metis exhibit these inferences⁶

Rule	Purpose
canonicalize	transforms formulas to CNF, DNF or NNF
clausify	performs clausification
conjunct	takes a formula from a conjunction
negate	applies negation to the formula
resolve	applies theorems of resolution
simplify	applies over a list of formula to simplify them
strip	splits a formula into subgoals

⁶Inference rules found in proofs of Propositional Logic theorems.

.tstp



A TSTP derivation⁷

- ▶ Is a **Directed Acyclic Graph** where
 - leaf** is a formula from the TPTP input
 - node** is a formula inferred from parent formula
 - root** the final derived formula
- ▶ Is a list of annotated formulas with the form

```
language(name, role, formula, source [,useful info]).
```

where **source** typically is an inference record

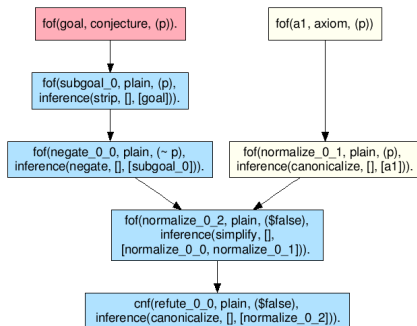
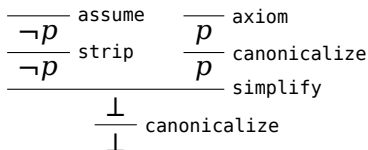
```
inference(rule, useful info, parents).
```

⁷<http://www.cs.miami.edu/~tptp/TPTP/QuickGuide/Derivations.html>.

- Proof found by Metis for the problem $p \vdash p$

```
$ metis --show proof problem.tptp
fof(a, axiom, p).
fof(goal, conjecture, p).
fof(subgoal_0, plain, p),
    inference(strip, [], [goal])).
fof(negate_0_0, plain, ~ p,
    inference(negate, [], [subgoal_0])).
fof(normalize_0_0, plain, ~ p,
    inference(canonicalize, [], [negate_0_0])).
fof(normalize_0_1, plain, p,
    inference(canonicalize, [], [a])).
fof(normalize_0_2, plain, $false,
    inference(simplify, [],
        [normalize_0_0, normalize_0_1])).
cnf(refute_0_0, plain, $false,
    inference(canonicalize, [], [normalize_0_2])).
```

By refutation, we proved $p \vdash p$:



Is a `Haskell` program that translates proofs given by `Metis` in TSTP format to `Agda` code

- ▶ Parsing of TSTP language⁸
- ▶ Creation⁸ and analysis of **DAG** derivations
- ▶ Analysis of inference rules used in the TSTP derivation
- ▶ `Agda` code generation

Library	Purpose
<code>Agda - Prop</code>	axioms and theorems of Classical Propositional Logic
<code>Agda - Metis</code>	versions of the inference rules used by <code>Metis</code>

⁸<https://github.com/agomezl/tstp2agda>.

- ▶ Intuitionistic Propositional Logic + PEM ($\Gamma \vdash \phi \vee \neg\phi$)
- ▶ A data type for formulas

```
data Prop : Set where
  Var  : Fin n → Prop
  T    : Prop
  ⊥    : Prop
  _∧_  : (φ ψ : Prop) → Prop
  _∨_  : (φ ψ : Prop) → Prop
  _⇒_  : (φ ψ : Prop) → Prop
  _⇔_  : (φ ψ : Prop) → Prop
  ¬_   : (φ : Prop) → Prop
```

⁹<https://github.com/jonaprieto/agda-prop>.

- ▶ A data type for theorems

```
data _⊢_ : (Γ : Ctxt)(φ : Prop) → Set
```

- ▶ Constructors

```
assume, axiom, weaken, ⊤-intro, ⊥-elim, ¬-intro,  
¬-elim, ∧-intro, ∧-proj1, ∧-proj2, ∨-intro1,  
∨-intro2, ∨-elim, ⇒-intro, ⇒-elim, ⇔-intro,  
⇔-elim1, ⇔-elim2.
```

- ▶ Natural deduction proofs for more than 71 theorems

```
⇔-equiv, ⇔-assoc, ⇔-comm, ⇒-⇔-∨, ⇔-¬-to-¬,  
¬⇔-to-¬, ¬¬-equiv, ⇒-⇔-∧, ⇔-trans, ∧-assoc,  
∧-comm, ∧-dist, ¬∧-to-¬∨, ¬∨¬-to-¬∧, ¬∨¬-⇔-¬∧,  
subst-∧1, subst-∧2, ∨-assoc, ∨-comm, ∨-dist,  
∨-equiv, ¬∨-to-¬∧, ¬∧¬-to-¬∨, ∨-dmorgan,  
¬∨¬¬-to-∨, cnf, nnf, dnf, RAA, ...
```

Rule	Purpose	Theorem
<code>canonicalize</code>	transforms formulas to CNF, DNF or NNF	<code>atp-canonicalize</code>
<code>clausify</code>	performs clausification	<code>atp-clausify</code>
<code>conjunct</code>	takes a formula from a conjunction	<code>atp-conjunct</code>
<code>negate</code>	append negation symbol to the formula	<code>atp-negate</code>
<code>resolve</code>	applies theorems of resolution	<code>atp-resolve</code>
<code>simplify</code>	applies over a list of formula to simplify them	<code>atp-simplify</code>
<code>strip</code>	splits a formula into subgoals	<code>atp-strip</code>

► Definition

$$\text{conjunct}(\overbrace{\varphi_1 \wedge \cdots \wedge \varphi_n}^{\varphi}, \psi) = \begin{cases} \varphi_i & \text{if } \psi \text{ is equal to some } \varphi_i \\ \varphi & \text{otherwise} \end{cases}$$

¹⁰<https://github.com/jonaprieto/agda-metis>.

► Definition

$$\text{conjunct}(\overbrace{\varphi_1 \wedge \cdots \wedge \varphi_n}^{\varphi}, \psi) = \begin{cases} \varphi_i & \text{if } \psi \text{ is equal to some } \varphi_i \\ \varphi & \text{otherwise} \end{cases}$$

► Inference rules involved

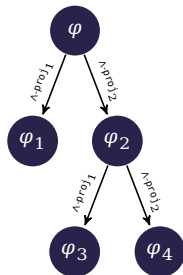
$$\frac{\varphi_1 \wedge \varphi_2}{\varphi_1} \wedge\text{-proj}_1$$

$$\frac{\varphi_1 \wedge \varphi_2}{\varphi_2} \wedge\text{-proj}_2$$

► Example

$$\varphi := \varphi_1 \wedge \overbrace{(\varphi_3 \wedge \varphi_4)}^{\varphi_2}$$

- $\text{conjunct}(\varphi, \varphi_3 \wedge \varphi_1) \equiv \varphi$
- $\text{conjunct}(\varphi, \varphi_3) \equiv \varphi_3$
- $\text{conjunct}(\varphi, \varphi_2) \equiv \varphi_2$



¹⁰<https://github.com/jonaprieto/agda-metis>.

```

data ConjView : Prop → Set where
  conj  : ( $\phi_1 \ \phi_2$  : Prop) → ConjView ( $\phi_1 \wedge \phi_2$ )
  other : ( $\phi$  : Prop)      → ConjView  $\phi$ 

```

```

conj-view : ( $\phi$  : Prop) → ConjView  $\phi$ 
conj-view ( $\phi \wedge \psi$ ) = conj _ _
conj-view  $\phi$        = other _

```

```

data Step : Set where
  pick  : Step
  proj1 : Step
  proj2 : Step

```

```

Path : Set
Path = List Step

```

```

conjunct-path : ( $\phi \ \psi$  : Prop) → Path → Path
conjunct-path  $\phi \ \psi$  path with [ eq  $\phi \ \psi$  ]
... | true  = path ::r pick
... | false with conj-view  $\phi$ 
...   | other _ = []
...   | conj  $\phi_1 \ \phi_2$  with conjunct-path  $\phi_1 \ \psi$  []
...     | subpath@(_ :: _) = (path ::r proj1) ++ subpath
...     | [] with conjunct-path  $\phi_2 \ \psi$  []
...       | subpath@(_ :: _) = (path ::r proj2) ++ subpath
...       | []              = []

```

The `conjunct` function and its theorem, `atp-conjunct`

`conjunct : Prop → Prop → Prop`

`conjunct φ ψ with conj-view φ | conjunct-path φ ψ []`

...		—		[]	=	φ
...		conj — —		pick :: —	=	φ
...		conj φ ₁ —		proj ₁ :: —	=	conjunct φ ₁ ψ
...		conj — φ ₂		proj ₂ :: —	=	conjunct φ ₂ ψ
...		other .φ		—	=	φ

`atp-conjunct`

`: ∀ {Γ} {φ}`

`→ (ψ : Prop)`

`→ Γ ⊢ φ`

`→ Γ ⊢ conjunct φ ψ`

`atp-conjunct {Γ} {φ} ψ Γ ⊢ φ`

`with conj-view φ | conjunct-path φ ψ []`

...		—		[]	=	Γ ⊢ φ
...		conj — —		pick :: —	=	Γ ⊢ φ
...		conj — —		proj ₁ :: —	=	atp-conjunct ψ (λ-proj ₁ Γ ⊢ φ)
...		conj — —		proj ₂ :: —	=	atp-conjunct ψ (λ-proj ₂ Γ ⊢ φ)
...		other —		(_ :: _)	=	Γ ⊢ φ

- ▶ The problem is $p \wedge q \vdash q \wedge p$
- ▶ In TPTP format

```
$ cat problem.tptp  
fof(a, axiom, p & q).  
fof(goal, conjecture, q & p).
```

- ▶ How to use Athena with your problem

```
$ metis --show proof problem.tptp > problem.tstp  
$ athena problem.tstp  
$ agda problem.tstp
```

```

fof(a, axiom, p & q).
fof(goal, conjecture, q & p).
fof(subgoal_0, plain, q,
    inference(strip, [], [goal])).
fof(subgoal_1, plain, q => p,
    inference(strip, [], [goal])).
fof(negate_0_0, plain, ~ q,
    inference(negate, [], [subgoal_0])).
fof(normalize_0_0, plain, (~ q),
    inference(canonicalize, [], [negate_0_0])).
fof(normalize_0_1, plain, p & q,
    inference(canonicalize, [], [a])).
fof(normalize_0_2, plain, q,
    inference(conjunct, [], [normalize_0_1])).
fof(normalize_0_3, plain, $false,
    inference(simplify, [],
        [normalize_0_0, normalize_0_2])).
cnf(refute_0_0, plain, $false,
    inference(canonicalize, [], [normalize_0_3])).
fof(negate_1_0, plain, ~ (q => p),
    inference(negate, [], [subgoal_1])).
fof(normalize_1_0, plain, ~ p & q,

```

```
    inference(canonicalize, [], [negate_1_0])).  
fof(normalize_1_1, plain, p & q,  
    inference(canonicalize, [], [a])).  
fof(normalize_1_2, plain, p,  
    inference(conjunct, [], [normalize_1_1])).  
fof(normalize_1_3, plain, q,  
    inference(conjunct, [], [normalize_1_1])).  
fof(normalize_1_4, plain, $false,  
    inference(simplify, [],  
        [normalize_1_0, normalize_1_2, normalize_1_3])).  
cnf(refute_1_0, plain, ($false),  
    inference(canonicalize, [], [normalize_1_4])).
```

Problem $p \wedge q \vdash q \wedge p$

Proof generated with Athena

```
p, q, a, goal, subgoal0, subgoal1 : Prop

-- Axiom.
a = p ∧ q

-- Premise.
Γ : Ctxt
Γ = [ a ]

-- Conjecture.
goal = q ∧ p

-- Subgoals.
subgoal0 = q
subgoal1 = q ⇒ p
```


Problem $p \wedge q \vdash q \wedge p$

Reconstructed Proof

```
a : Prop
a = p ∧ q

subgoal₀ : Prop
subgoal₀ = q

proof₀ : Γ ⊢ subgoal₀
proof₀ =
  (RAA
    (atp-simplify ⊥
      (assume {Γ = Γ}
        (¬ subgoal₀))
      (atp-conjunct q
        (atp-canonicalize (p ∧ q)
          (weaken (¬ subgoal₀)
            (assume {Γ = ∅} a)))))))
```

Problem $p \wedge q \vdash q \wedge p$

Reconstructed Proof

```
subgoal1 : Prop
subgoal1 = q ⇒ p

proof1 : Γ ⊢ subgoal1
proof1 =
  (RAA
    (atp-simplify ⊥
      (atp-conjunct q
        (atp-canonicalize (p ∧ q)
          (weaken (¬ subgoal1)
            (assume {Γ = ∅} a))))))
    (atp-simplify ⊥
      (atp-canonicalize ((¬ p) ∧ q)
        (assume {Γ = Γ}
          (¬ subgoal1))))
    (atp-conjunct p
      (atp-canonicalize (p ∧ q)
        (weaken (¬ subgoal1)
          (assume {Γ = ∅} a))))))
```

Problem $p \wedge q \vdash q \wedge p$

Reconstructed proof

```
-- Premise.  
 $\Gamma = [ a ]$   
  
-- Conjecture.  
goal =  $q \wedge p$   
  
-- Subgoals.  
subgoal0 =  $q$   
subgoal1 =  $q \Rightarrow p$   
  
-- Proof  
proof0 :  $\Gamma \vdash \text{subgoal}_0$   
proof1 :  $\Gamma \vdash \text{subgoal}_1$   
  
proof :  $\Gamma \vdash \text{goal}$   
proof =  
   $\Rightarrow$ -elim  
    atp-splitGoal --  $q \wedge (q \Rightarrow p) \Rightarrow p$   
    ( $\wedge$ -intro proof0 proof1)
```

Bug¹¹ in the Printing of the Proof

Metis v2.3 (release 20161108)

```
$ cat problem.tptp
fof(goal, conjecture,
  ((p <=> q) <=> r) <=> (p <=> (q <=> r))).
```

```
$ metis --show proof problem.tptp
...
fof(normalize_2_0, plain,
  (~ p & (~ q <=> ~ r) & (~ p <=> (~ q <=> ~ r))),
  inference(canonicalize, [], [negate_2_0])).
fof(normalize_2_1, plain, ~ p <=> (~ q <=> ~ r),
  inference(conjunct, [], [normalize_2_0])).
fof(normalize_2_2, plain, ~ q <=> ~ r,
  inference(conjunct, [], [normalize_2_0])).
fof(normalize_2_3, plain, ~ p,
  inference(conjunct, [], [normalize_2_0])).
fof(normalize_2_4, plain, $false,
  inference(simplify, [],
    [normalize_2_1, normalize_2_2, normalize_2_3])).
...
```

¹¹<https://github.com/gilith/metis/issues/2>.

$$\varphi := \neg p \wedge (\neg q \Leftrightarrow \neg r) \wedge (\neg p \Leftrightarrow (\neg q \Leftrightarrow \neg r))$$

$$\frac{\frac{\frac{\vdots}{\varphi} \text{ canonicalize}}{\neg p \Leftrightarrow (\neg q \Leftrightarrow \neg r)} \text{ conjunct} \quad \frac{\frac{\frac{\vdots}{\varphi} \text{ canonicalize}}{\neg q \Leftrightarrow \neg r} \text{ conjunct} \quad \frac{\frac{\frac{\vdots}{\varphi} \text{ canonicalize}}{\neg p} \text{ conjunct}}{\neg p} \text{ simplify}}{\perp}$$

$$\varphi := \neg p \wedge (\neg q \Leftrightarrow \neg r) \wedge (\neg p \Leftrightarrow (\neg q \Leftrightarrow \neg r))$$

$$\frac{\frac{\frac{\vdots}{\varphi} \text{ canonicalize}}{\neg p \Leftrightarrow (\neg q \Leftrightarrow \neg r)} \text{ conjunct} \quad \frac{\frac{\frac{\vdots}{\varphi} \text{ canonicalize}}{\neg q \Leftrightarrow \neg r} \text{ conjunct} \quad \frac{\frac{\frac{\vdots}{\varphi} \text{ canonicalize}}{\neg p} \text{ conjunct}}{\neg p} \text{ simplify}}{\perp}$$

The bug was caused by the conversion of `Xor` sets to `Iff` lists. After reporting this, Hurd fixed the printing of `canonicalize` inference rule

$$\varphi := \neg p \wedge (\neg q \Leftrightarrow \neg r) \wedge (\neg p \Leftrightarrow (\neg q \Leftrightarrow r))$$

SledgeHammer

(Paulson and Susanto, 2007)

- ▶ Isabelle/HOL mature tool
- ▶ Metis ported within Isabelle/HOL
- ▶ Reconstruct proofs of well-known ATPs: EProver, Vampire, among others using SystemOnTPTP server

Integrating Waldmeister into Agda

(Foster and Struth, 2011)

- ▶ Framework for a integration between Agda and ATPs
 - ▶ Equational Logic
 - ▶ Reflection Layers
- ▶ Source code is not available¹²

¹²<http://simon-foster.staff.shef.ac.uk/agdaatp>.

At the moment, the communication between Agda and the ATPs is unidirectional because the ATPs are being used as oracles (Sicard-Ramírez, Bove, and Dybjer, 2015)

```
module Or where
```

```
data _v_ (A B : Set) : Set where
```

```
  inj₁ : A → A v B
```

```
  inj₂ : B → A v B
```

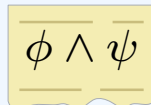
```
postulate
```

```
  A B      : Set
```

```
  v-comm : A v B → B v A
```

```
{-# ATP prove v-comm #-}
```

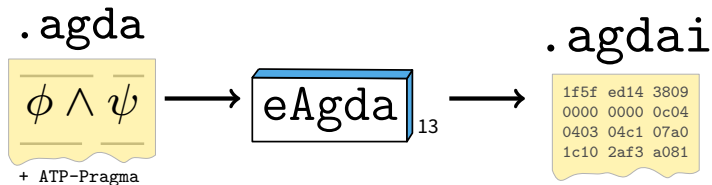
.agda



+ ATP-Pragma

Related Work: Apia

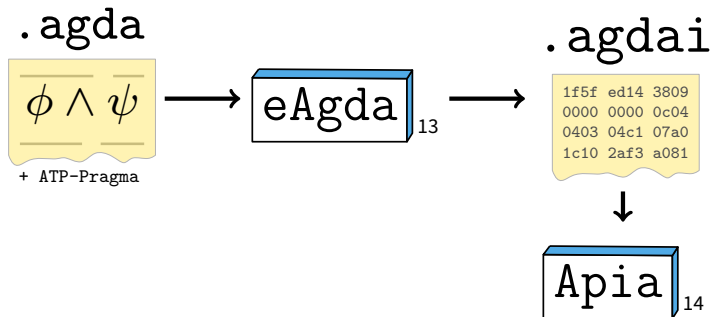
Proving First-Order theorems written in Agda using automatic theorem provers for First-Order Logic



¹³<https://github.com/asr/eagda>.

Related Work: Apia

Proving First-Order theorems written in Agda using automatic theorem provers for First-Order Logic

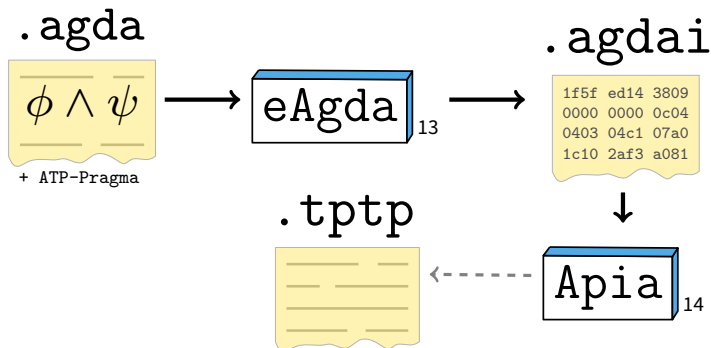


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¹⁴<https://github.com/asr/apia>.

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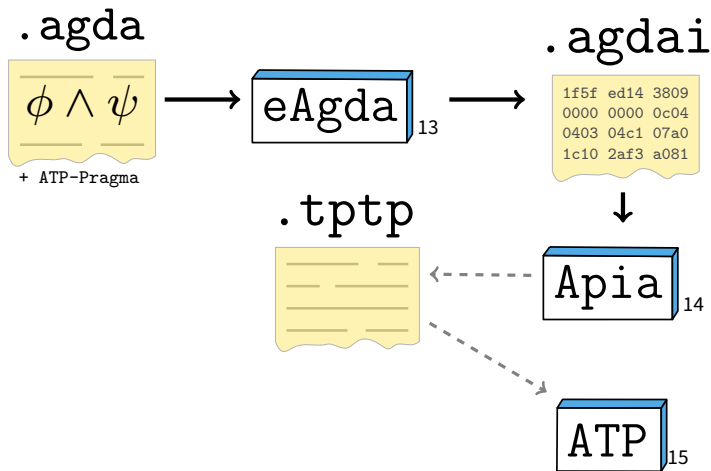


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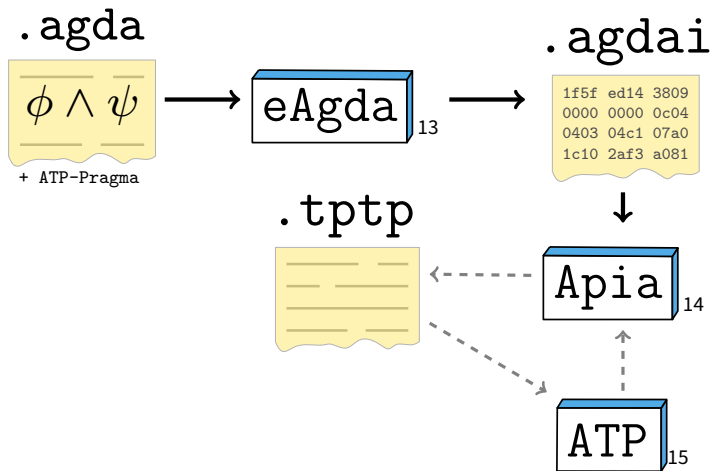
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¹⁴<https://github.com/asr/apia>.

¹⁵<http://github.com/jonaprieto/online-atps>.

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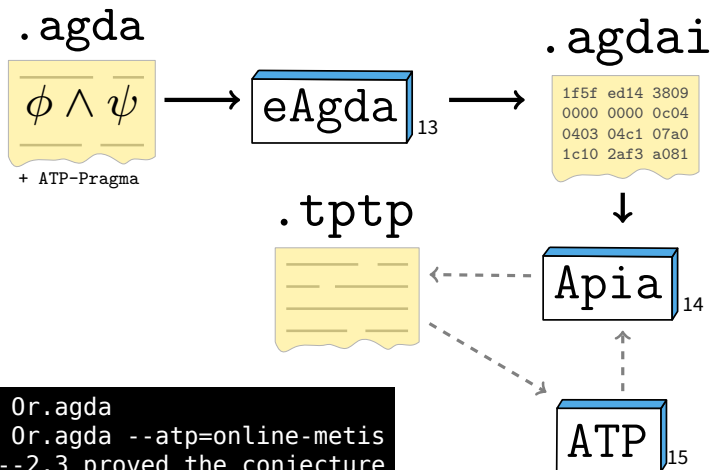
¹³<https://github.com/asr/eagda>.

¹⁴<https://github.com/asr/apia>.

¹⁵<http://github.com/jonaprieto/online-atps>.

Related Work: Apia

Proving First-Order theorems written in Agda using automatic theorem provers for First-Order Logic



¹³<https://github.com/asr/eagda>.

¹⁴<https://github.com/asr/apia>.

¹⁵<http://github.com/jonaprieto/online-atps>.

- ▶ Complete implementation for `simplify` inference¹⁶
- ▶ Complete implementation for `canonicalize` inference: what normal form use to transform the formulas
- ▶ Complete implementation for Splitting a goal in a list of subgoals

¹⁶<https://github.com/gilith/metis/issues/3>.

Name	References
Agda-Metis	(Prieto-Cubides and Sicard-Ramírez, 2017a)
Agda-Prop	(Prieto-Cubides and Sicard-Ramírez, 2017b)
Athena	(Prieto-Cubides and Sicard-Ramírez, 2017c)
OnlineATPs	(Prieto-Cubides, 2017a)
Prop-Pack	(Prieto-Cubides, 2017b)

- ▶ Integration with Apia
- ▶ Support First-Order Logic with Equality
- ▶ Support another prover like EProver or Vampire









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$$\frac{}{C} \text{ axiom}$$

$$\frac{}{L \vee \neg L} \text{ assume } L$$

$$\frac{C}{\sigma C} \text{ subst } \sigma$$

$$\frac{L \vee C \quad \neg L \vee D}{C \vee D} \text{ resolve } L$$

$$\frac{}{t = t} \text{ refl } t$$

$$\frac{}{\neg(L[p] = t) \vee \neg L \vee L[p \mapsto t]} \text{ eq } L \ p \ t$$