# Proof Reconstruction in Classical Propositional Logic

(Work in Progress)

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Agda Implementors' Meeting XXV
May 9-15th 2017

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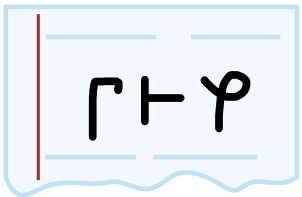
# Proof Reconstruction: Overview

A problem



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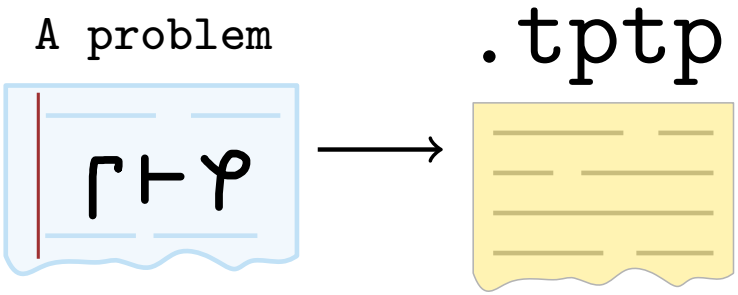

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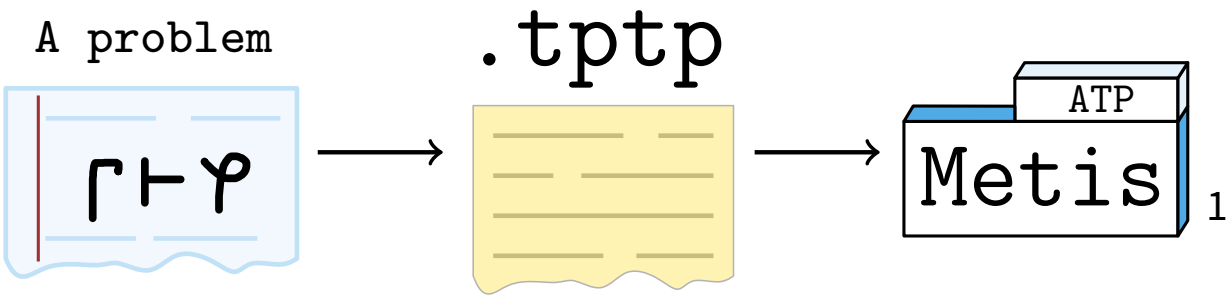


[1] http://www.gilith.com/software/metis

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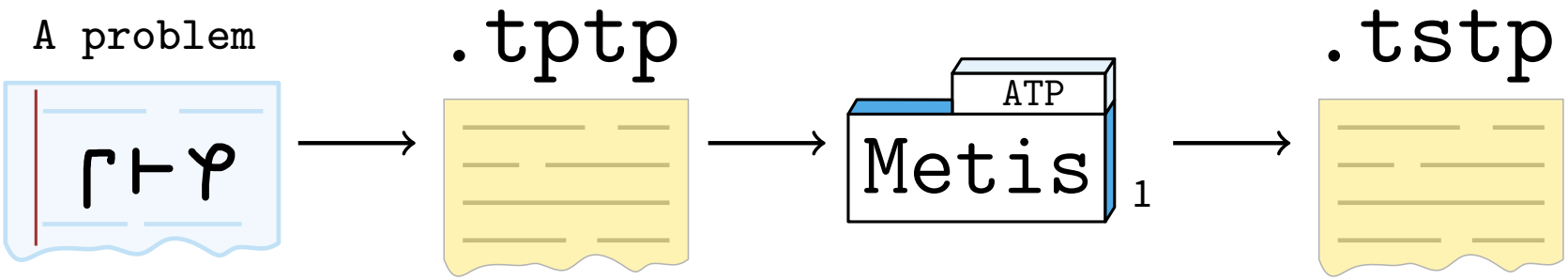


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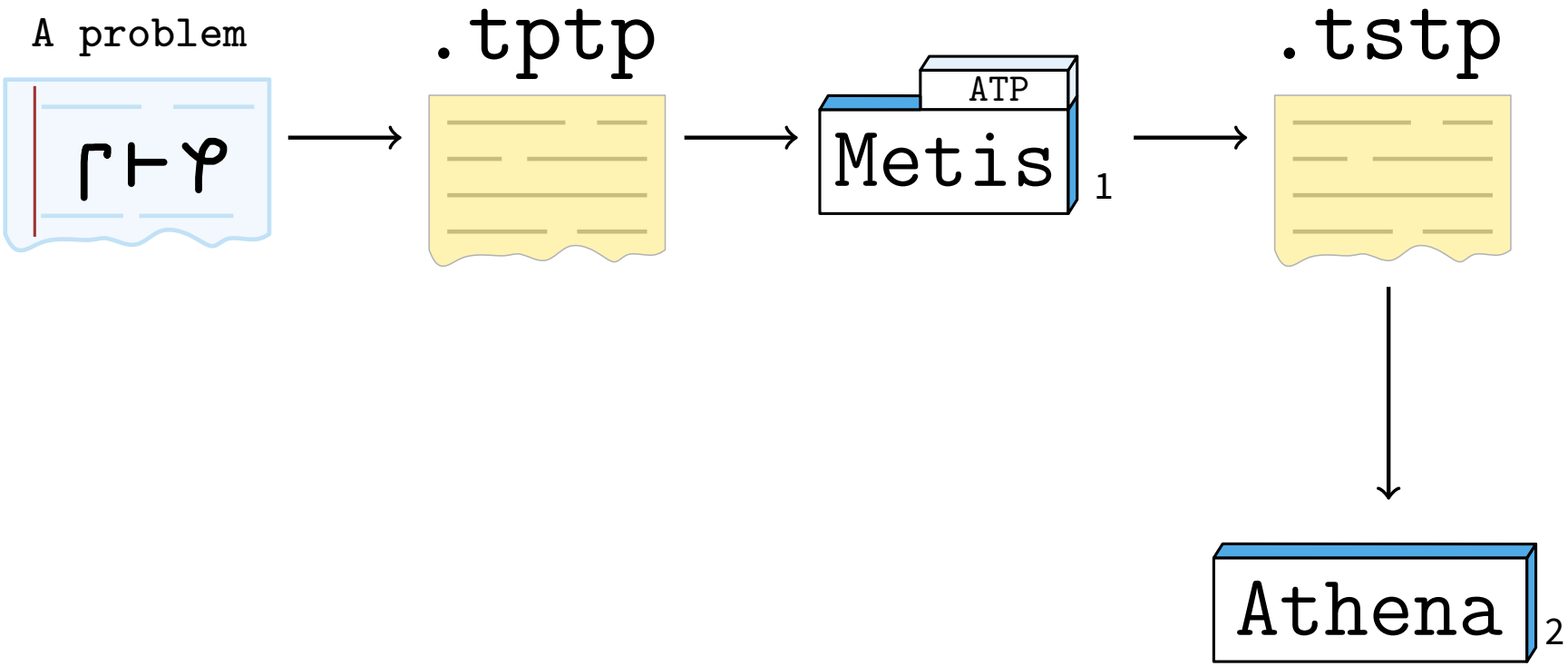


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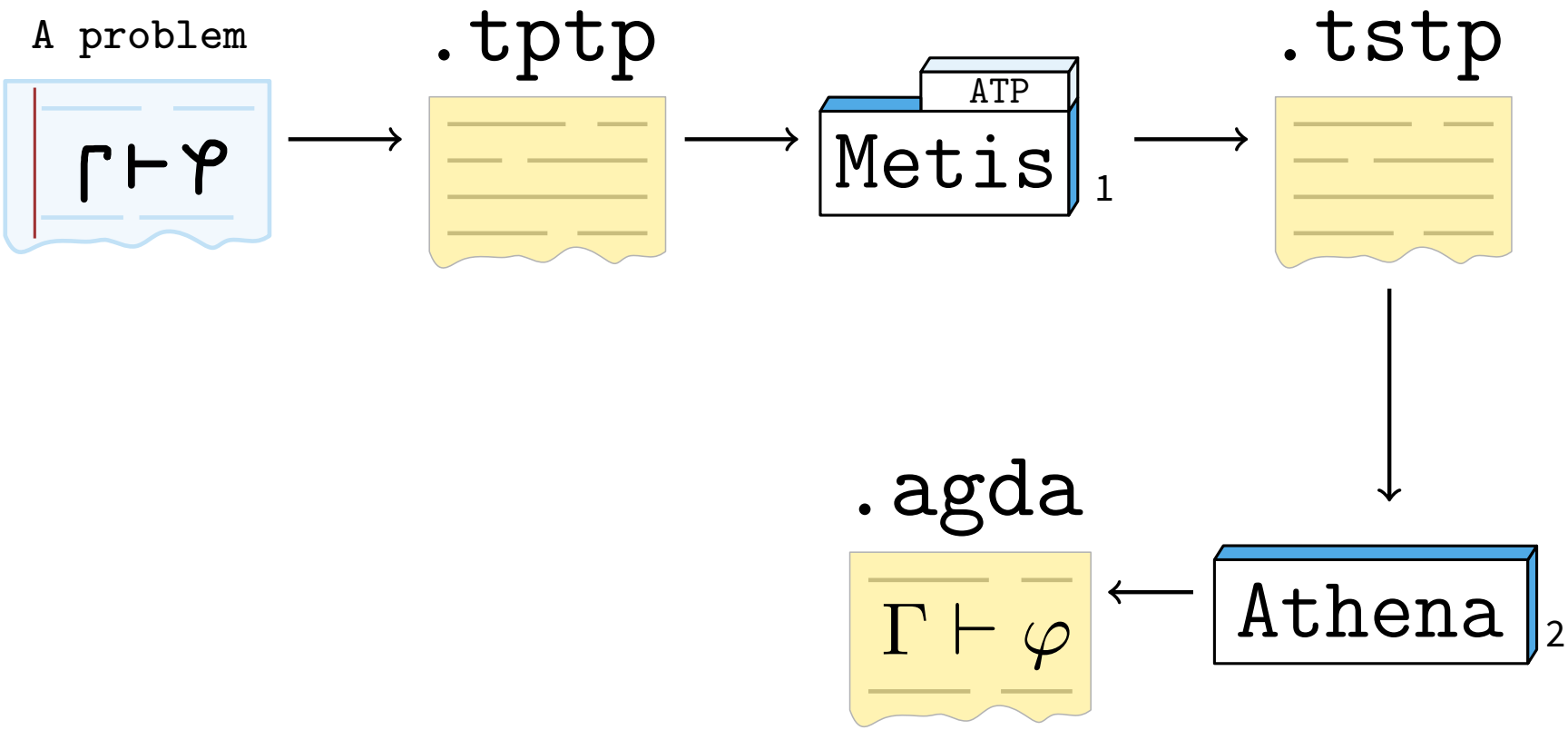


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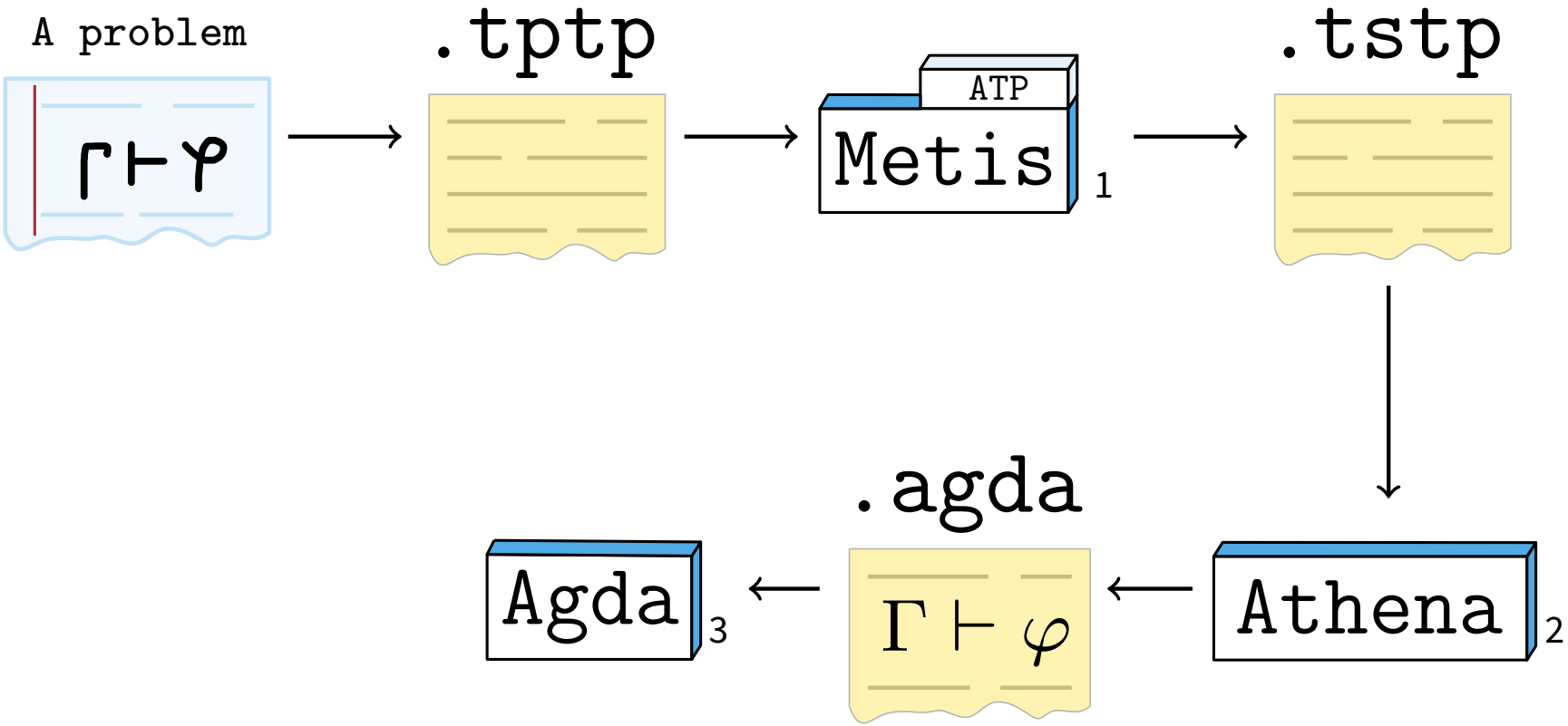


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[3] http://github.com/agda/agda

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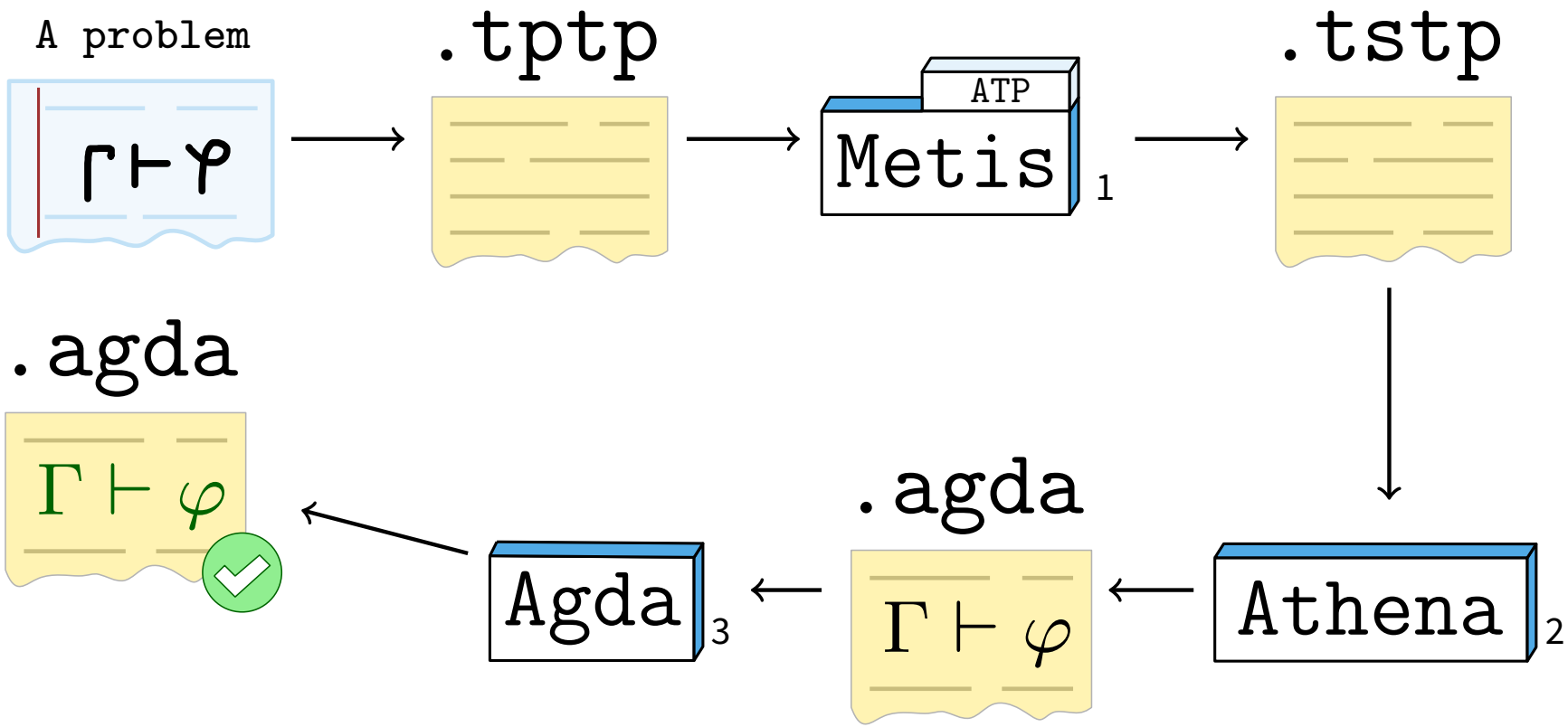


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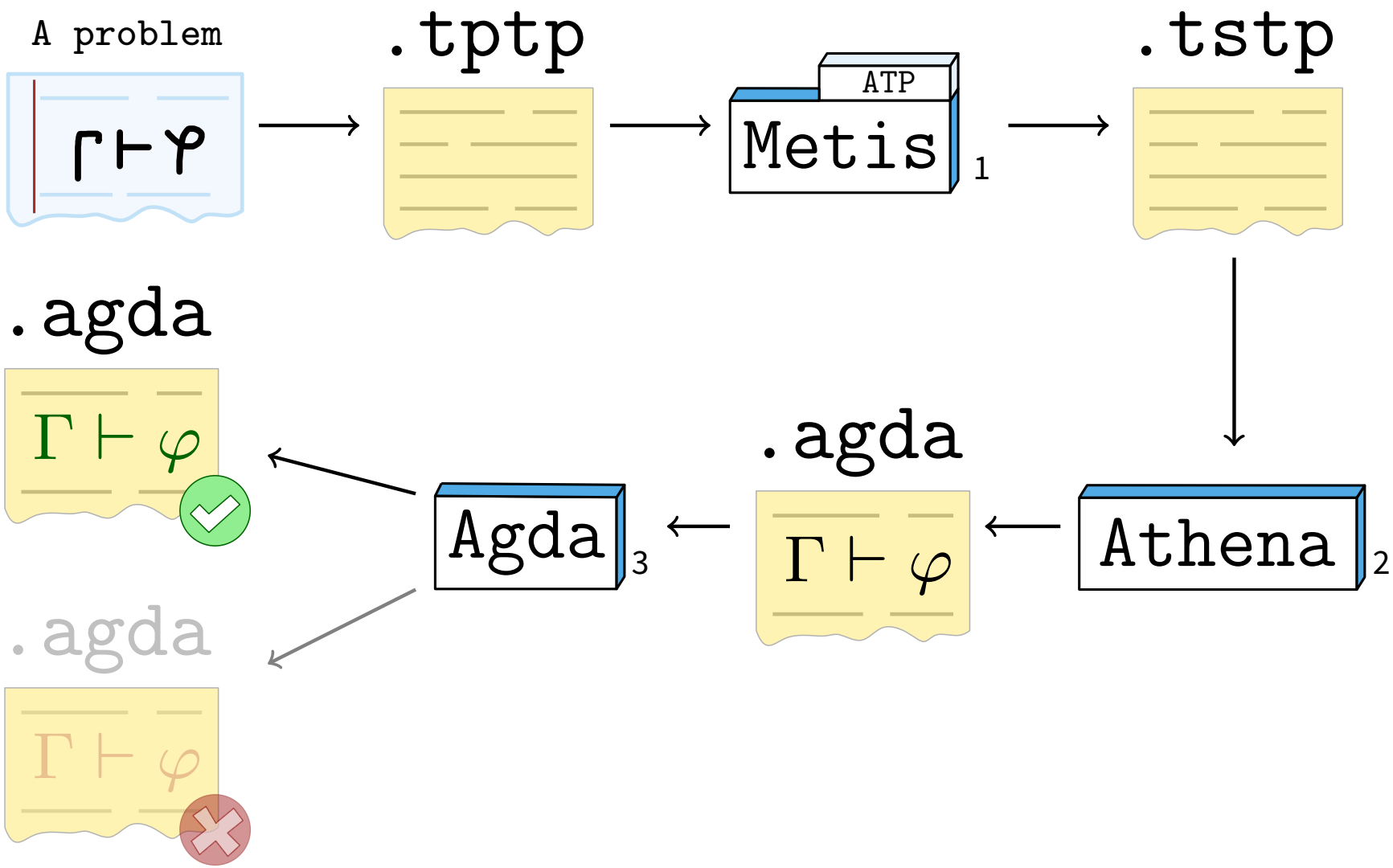


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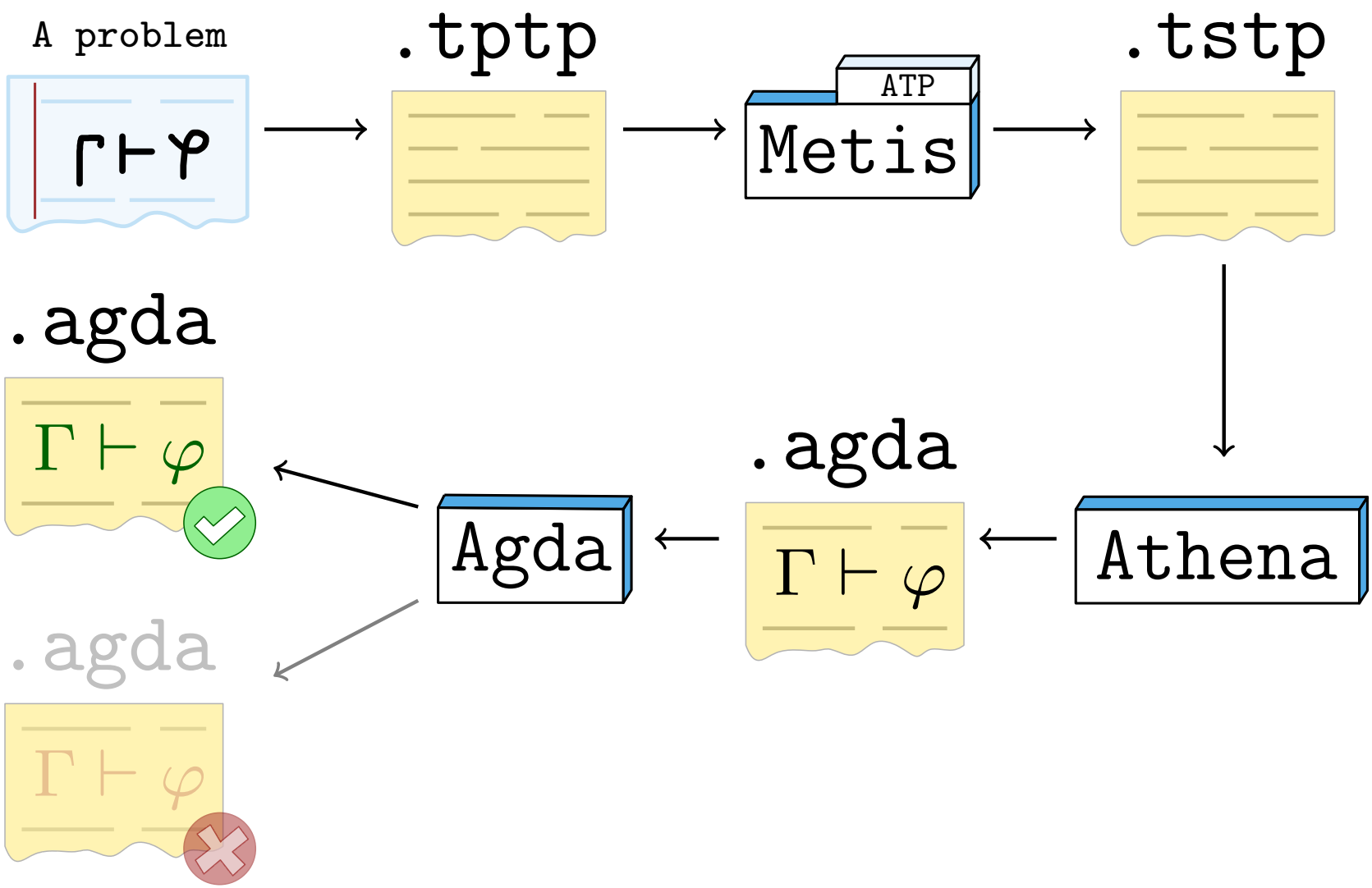

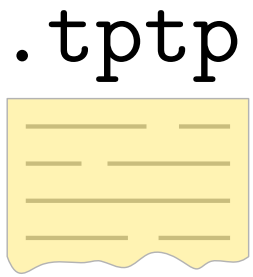


- Is a language[4] to encode problems (Sutcliffe, 2009)
- Is the input of the ATPs
- Annotated formulas with the form

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

| | |
|---|---|
| `language` | FOF or CNF |
| `name` | to identify the formula within the problem |
| `role` | axiom, definition, hypothesis, conjecture |
| `formula` | version in TPTP format |

[4] http://www.cs.miami.edu/~tptp/TPTP/SyntaxBNF.html

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# TPTP Examples

- $p \vdash p$

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

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

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

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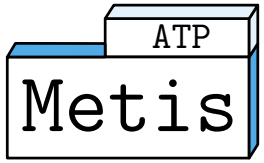


Metis is an automatic theorem prover for First-Order Logic with Equality (Hurd, 2003)

## 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/

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TSTP derivations by Metis exhibit these inferences [6]

| 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 |

[6] Inference rules found in proofs of Propositional Logic theorems

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.tstp

A TSTP derivation [7]

- Is a **D**irected **A**cyclic **G**raph 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

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# TSTP Example

- Proof found by `Metis` Prover 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])).
```

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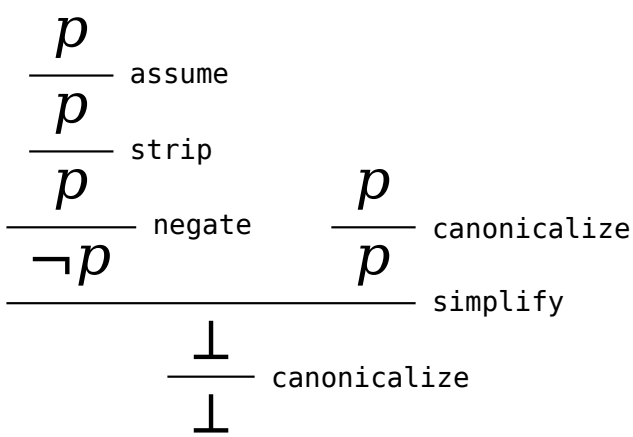
# DAG Example

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

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# Athena [10]

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

- Parsing of TSTP language[8,9]
- Creation[8] and analysis of **DAG** derivations
- Analysis of inference rules used in the TSTP derivation
- `Agda` code generation

| Library | Purpose |
|---|---|
| `Agda-Prop` | axioms and theorems of Classical Propositional Logic |
| `Agda-Metis` | versions of the inference rules used by `Metis` |

[8] https://github.com/agomezl/tstp2agda

[9] https://github.com/jonaprieto/tstp2agda

[10] http://github.com/jonaprieto/athena

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# Agda-Prop Library [11]

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

```
data Prop : Set where
  Var  : Fin n → Prop          -- Variables.
  ⊤    : Prop                  -- Top (truth).
  ⊥    : Prop                  -- Bottom (falsum).
  _∧_  : (φ ψ : Prop) → Prop   -- Conjunction.
  _∨_  : (φ ψ : Prop) → Prop   -- Disjunction.
  _⇒_  : (φ ψ : Prop) → Prop   -- Implication.
  _⇔_  : (φ ψ : Prop) → Prop   -- Biimplication.
  ¬_   : (φ : Prop)   → Prop   -- Negation.
```

[11] https://github.com/jonaprieto/agda-prop

# Agda-Prop Library [12]

- 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, ...
```

[12] https://github.com/jonaprieto/agda-prop

# Agda-Metis Library [13]

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

[13] `https://github.com/jonaprieto/agda-metis`

- Definition

$$\text{conjunct}(\phi_1 \wedge \phi_2 \wedge \cdots \wedge \varphi_i \wedge \cdots \wedge \phi_n, \varphi_i) \longrightarrow \varphi_i$$

- Function[14]:

```
conjunct : Prop → Prop → Prop
conjunct (φ ∧ ψ) ω with ⌊ eq φ ω ⌋ | ⌊ eq ψ ω ⌋
... | true  | _     = φ
... | false | true  = ψ
... | false | false = conjunct φ ω
conjunct φ ω        = φ
```

- Theorem[14]

```
atp-conjunct
  : ∀ {Γ} {φ}
  → (ω :Prop)
  → Γ ⊢ φ
  → Γ ⊢ conjunct φ ω
```

[14] Excerpt from the `Agda-Metis` library available in `ATP.Metis.Rules.Conjunct` module

[15] `https://github.com/jonaprieto/agda-metis`

# A proof of `atp-conjunct` theorem

```
atp-conjunct
  : ∀ {Γ} {φ}
  → (ω : Prop)
  → Γ ⊢ φ
  → Γ ⊢ conjunct φ ω

atp-conjunct {Γ} {φ ∧ ψ} ω Γ⊢φ
  with ⌊ eq φ ω ⌋ | ⌊ eq ψ ω ⌋
... | true  | _     = ∧-proj₁ Γ⊢φ
... | false | true  = ∧-proj₂ Γ⊢φ
... | false | false =
  atp-conjunct {Γ = Γ} {φ = φ} ω (∧-proj₁ Γ⊢φ)
atp-conjunct {_} {Var x}  _ = id
atp-conjunct {_} {⊤}      _ = id
atp-conjunct {_} {⊥}      _ = id
atp-conjunct {_} {φ ∨ ψ}  _ = id
atp-conjunct {_} {φ ⇒ ψ}  _ = id
atp-conjunct {_} {φ ⇔ ψ}  _ = id
atp-conjunct {_} {¬ φ}    _ = id
```

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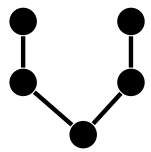
- The problem is $p \wedge q \vdash q \wedge p$
- In TPTP format

```
fof(a, axiom, p & q).
fof(goal, conjecture, q & p).
```

- A natural deduction proof

$$\dfrac{\dfrac{\phi \wedge \psi}{\phi}\,\wedge\text{-proj}_1 \qquad \dfrac{\phi \wedge \psi}{\psi}\,\wedge\text{-proj}_2}{\psi \wedge \phi}\,\wedge\text{-intro}$$



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# TSTP Derivation I

```
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,
```

# TSTP Derivation II

```
    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])).
```

```
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)
```

```
a : Prop
a = (p ∧ q)

subgoal₀ : Prop
subgoal₀ = q

proof₀ : Γ ⊢ subgoal₀
proof₀ =
  (RAA
    (atp-canonicalize
      (atp-simplify
        (atp-canonicalize
          (atp-strip
            (assume {Γ = Γ} (atp-negate subgoal₀))))
        (atp-conjunct (q)
          (atp-canonicalize
            (weaken (atp-negate subgoal₀)
              (assume {Γ = ∅} a)))))))
```

```
subgoal₁ : Prop
subgoal₁ = (q ⇒ p)

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

```
-- Premise.

Γ = [ a ]

-- Conjecture.

goal = (q ∧ p)

-- Subgoals.

subgoal₀ = q
subgoal₁ = (q ⇒ p)

-- Proof

proof₀ : Γ ⊢ subgoal₀
proof₁ : Γ ⊢ subgoal₁

proof : Γ ⊢ goal
proof =
  ⇒-elim
    atp-splitGoal                -- q ∧ (q ⇒ p) ⇒ p
    (∧-intro proof₀ proof₁)
```

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# Bug[16] 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])).
...
```

[16] https://github.com/gilith/metis/issues/2

# Bug in the Printing of the Proof

Metis' v2.3 (release 20161108) - Issue[17]

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

$$\dfrac{\dfrac{\dfrac{\vdots}{\varphi}\ \text{canonicalize}}{\neg p \Leftrightarrow (\neg q \Leftrightarrow \neg r)}\ \text{conjunct} \qquad \dfrac{\dfrac{\vdots}{\varphi}\ \text{canonicalize}}{\neg q \Leftrightarrow \neg r}\ \text{conjunct} \qquad \dfrac{\dfrac{\vdots}{\varphi}\ \text{canonicalize}}{\neg p}\ \text{conjunct}}{\bot}\ \text{simplify}$$

[17] https://github.com/gilith/metis/issues/2

# Bug in the Printing of the Proof

Metis' v2.3 (release 20161108) - Issue[17]

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

$$\dfrac{\dfrac{\dfrac{\vdots}{\varphi}\ \text{canonicalize}}{\neg p \Leftrightarrow (\neg q \Leftrightarrow \neg r)}\ \text{conjunct} \qquad \dfrac{\dfrac{\vdots}{\varphi}\ \text{canonicalize}}{\neg q \Leftrightarrow \neg r}\ \text{conjunct} \qquad \dfrac{\dfrac{\vdots}{\varphi}\ \text{canonicalize}}{\neg p}\ \text{conjunct}}{\bot}\ \text{simplify}$$

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

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

[17] https://github.com/gilith/metis/issues/2

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## SledgeHammer

(Paulson and Susanto, 2007)

- `Isabelle`/`HOL` mature tool
- `Metis` ported within `Isabelle`
- 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 available[18]

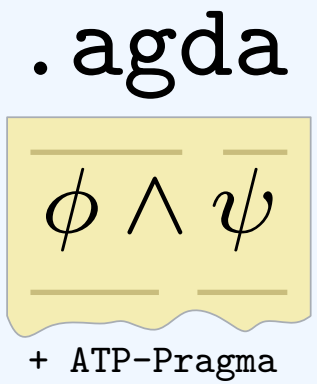
[18] `http://simon-foster.staff.shef.ac.uk/agdaatp`

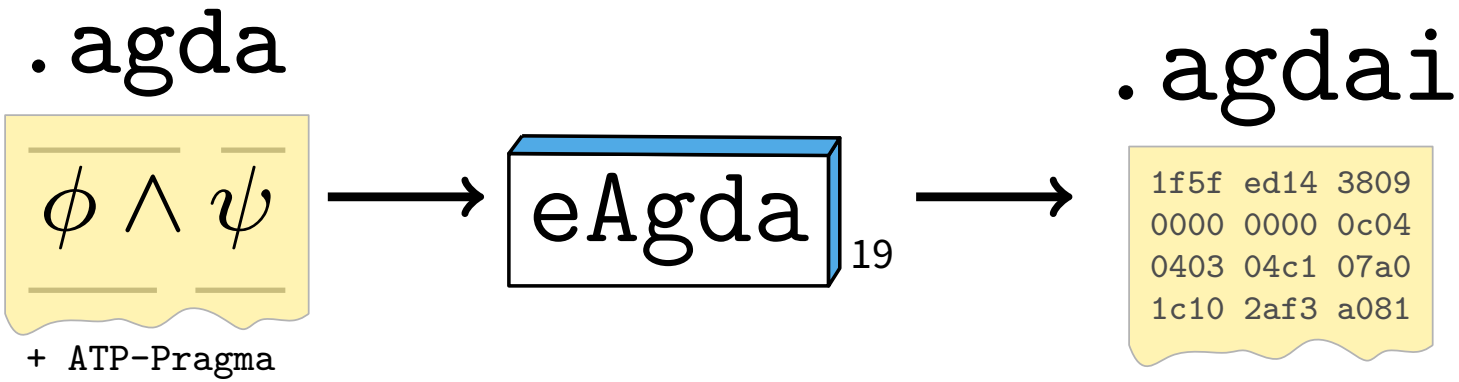
At the moment, the communication between Agda and the ATPs is unidirectional because the ATPs are being used as oracles (Sicard-Ramírez, Bove, and Dybjer, 2015)

```
module Or where

data _∨_ (A B : Set) : Set where
  inj₁ : A → A ∨ B
  inj₂ : B → A ∨ B

postulate
  A B    : Set
  ∨-comm : A ∨ B → B ∨ A
{-# ATP prove ∨-comm #-}
```

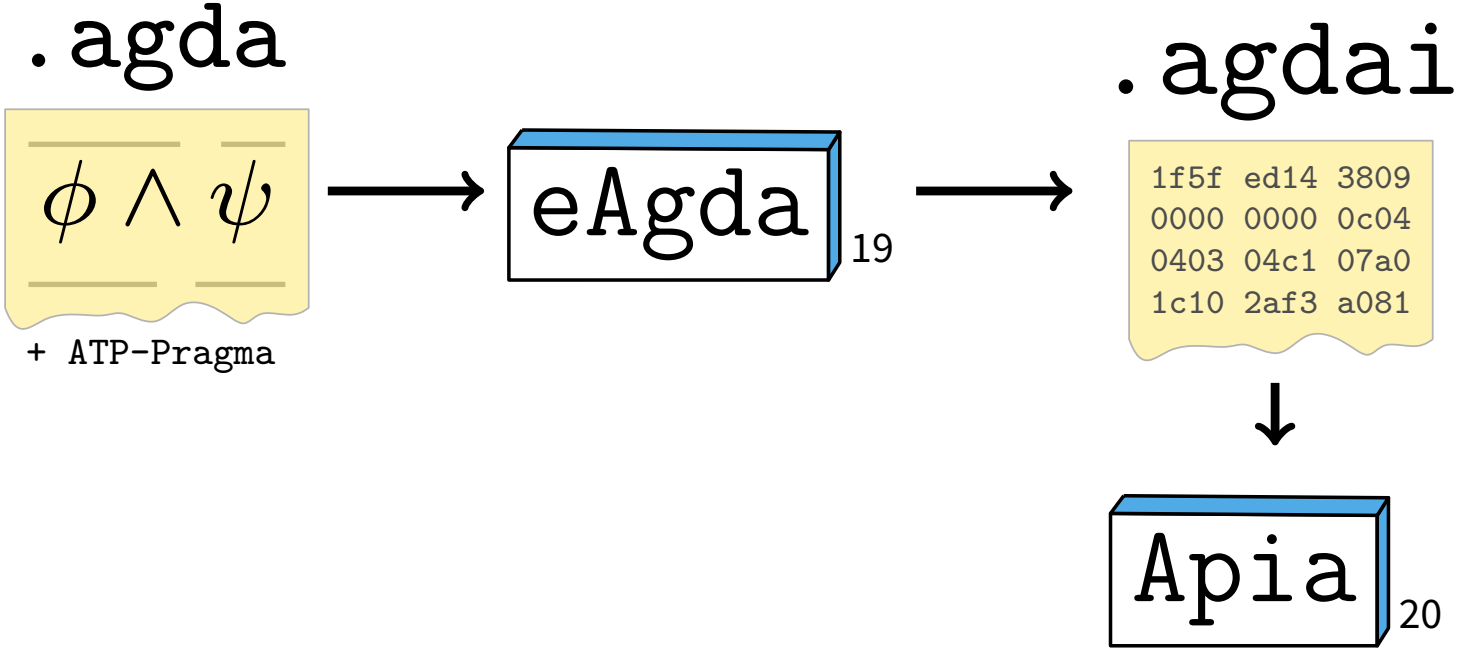





[19] https://github.com/asr/eagda

# Related Work: Apia

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

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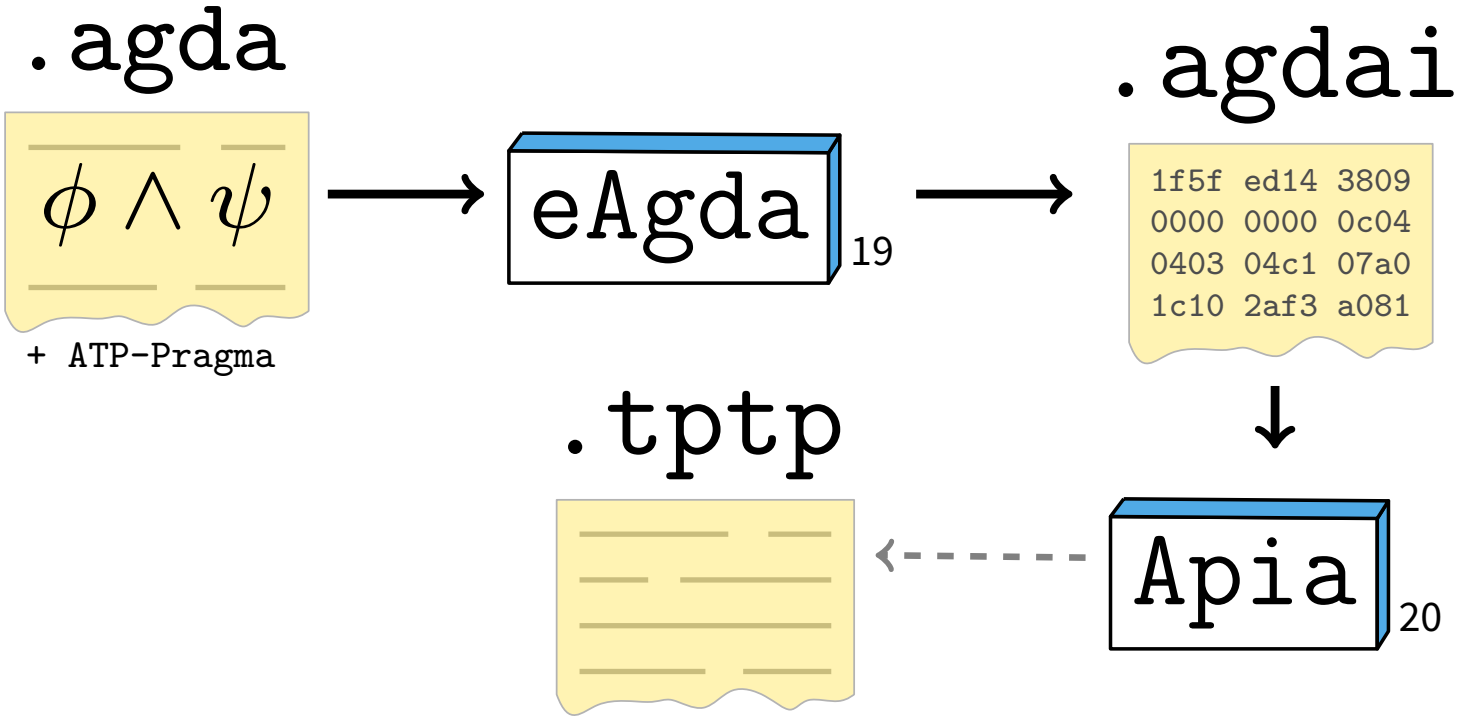


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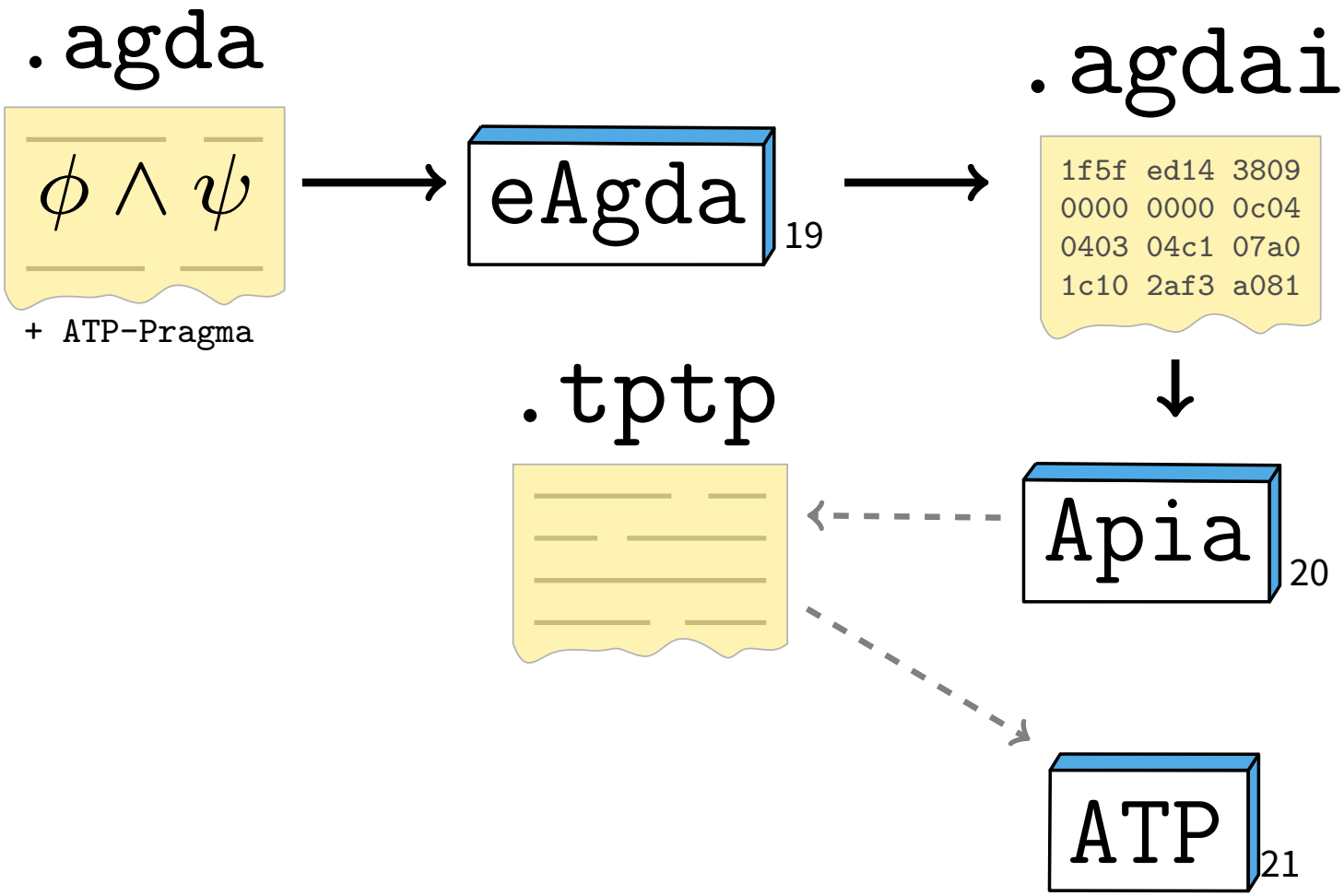


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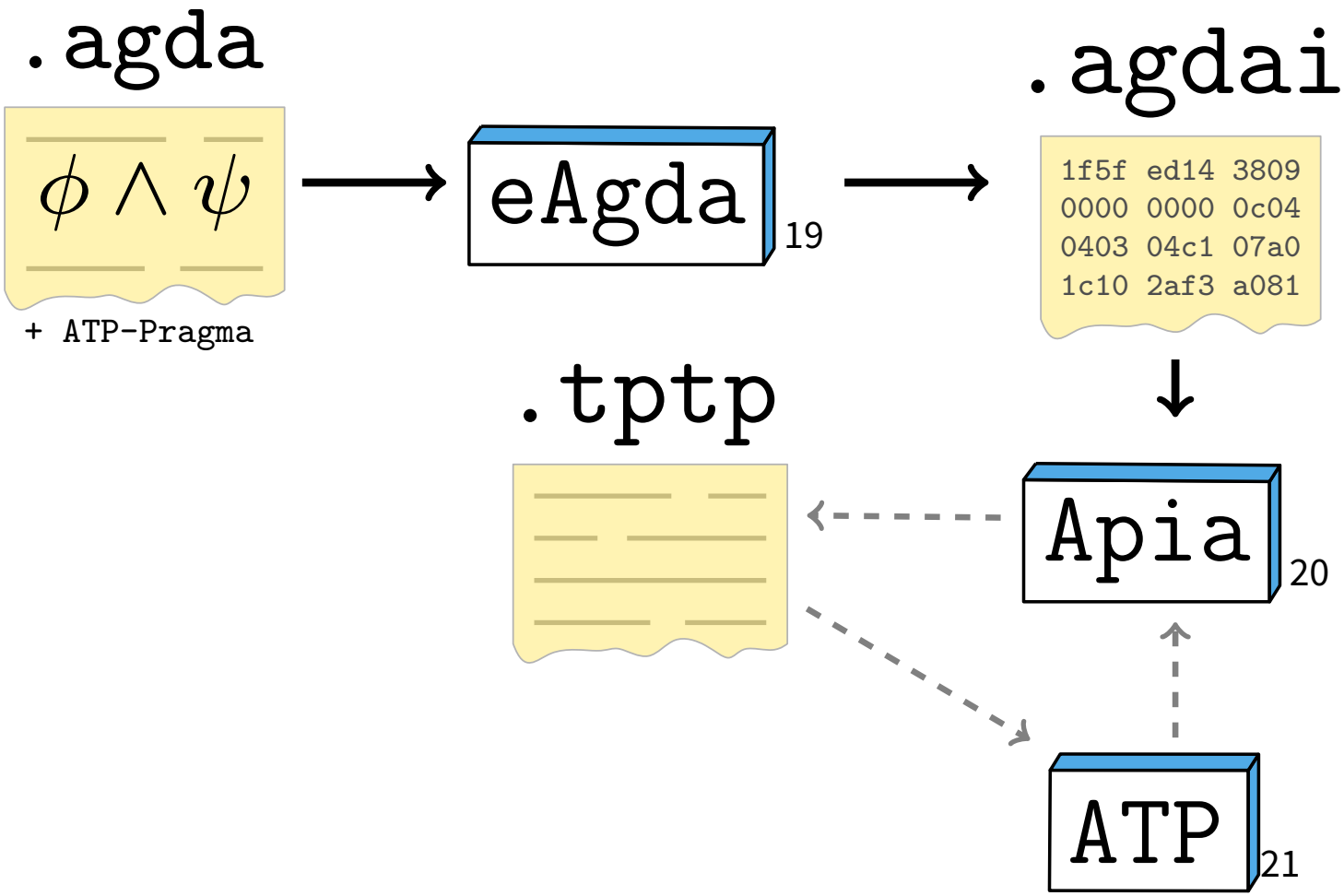


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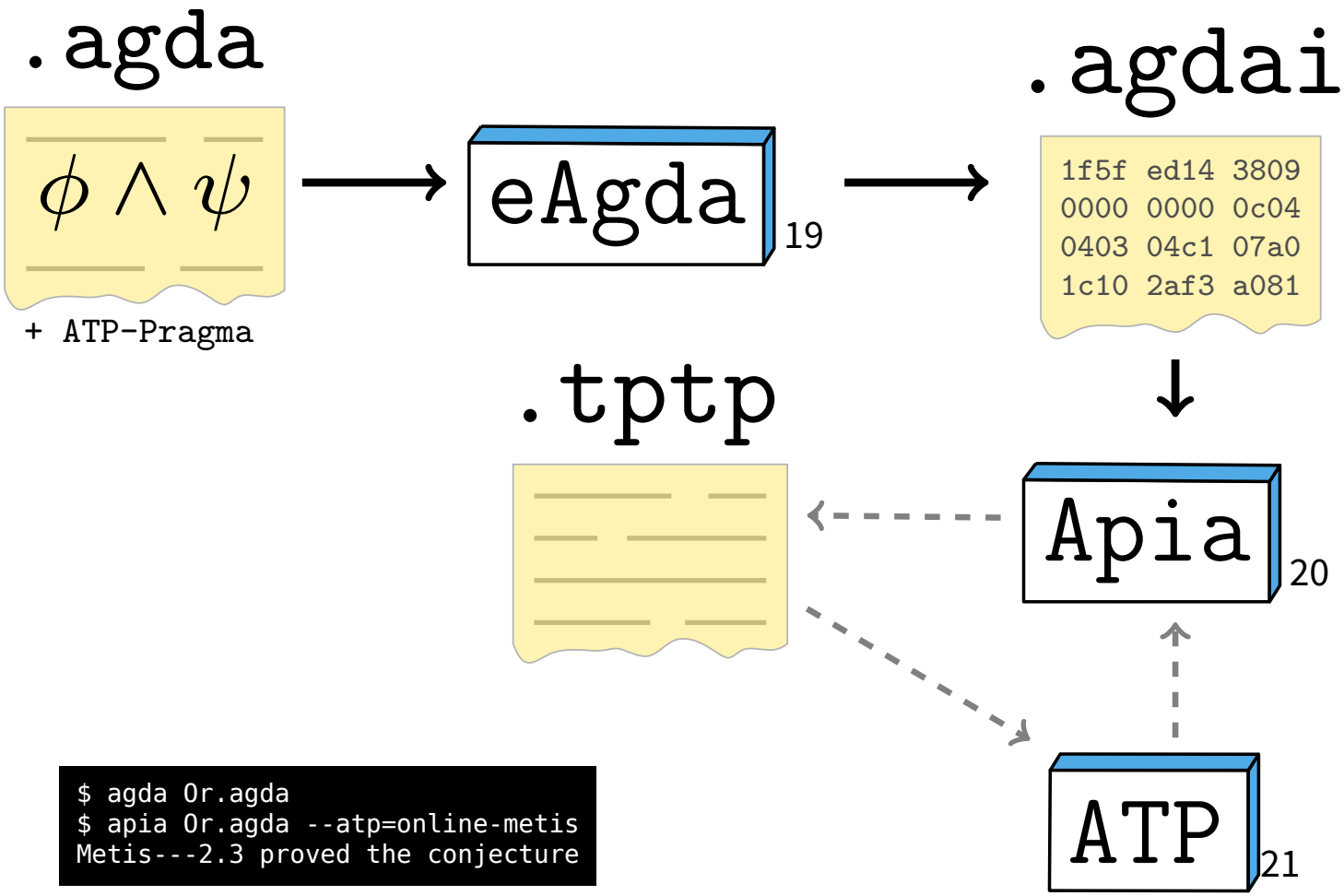


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# Pending Work

- Complete implementation for `simplify` inference[22]
- Complete implementation for `canonicalize` inference: what normal form use to transform the formulas
- Complete implementation for Splitting a goal in a list of subgoals

[22] `https://github.com/gilith/metis/issues/3`

| Name | Purpose |
|---|---|
| `Agda-Metis` | Implementation of `Metis`' inference rules |
| `Agda-Prop` | Syntax and theorems of Classical Propositional Logic |
| `Athena` | Translator for `Metis`' `TSTP` files to `Agda` |
| `OnlineATPs` | Client to use ATPs from `SystemOnTPTP` of `TPTP` World |
| `Prop-Pack` | Collection of `TPTP` problems to test `Athena` |

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

# References

Foster, Simon and Georg Struth (2011). “Integrating an Automated Theorem Prover into Agda”. In: *NASA Formal Methods: Third International Symposium, NFM 2011, Pasadena, CA, USA, April 18-20, 2011. Proceedings*. Ed. by Mihaela Bobaru et al. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 116–130.

Hurd, Joe (2003). “First-order proof tactics in higher-order logic theorem provers”. In: *Design and Application of Strategies/Tactics in Higher Order Logics, number NASA/CP-2003-212448 in NASA Technical Reports*, pp. 56–68.

Paulson, Lawrence C. and Kong Woei Susanto (2007). “Source-Level Proof Reconstruction for Interactive Theorem Proving”. In: *Theorem Proving in Higher Order Logics: 20th International Conference, TPHOLs 2007, Kaiserslautern, Germany, September 10-13, 2007. Proceedings*. Ed. by Klaus Schneider and Jens Brandt. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 232–245.

# Metis' Inference Rules

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

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

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

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

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

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

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