Plato: A Compiler for Web Forms

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Interactive Web Forms are the Norm

Today’s users expect web forms with two pieces of functionality:

• Implied value computation: given the user’s current information, what other information is obviously intended?

• Error Detection: which user-provided information is erroneous?

Benefits of in-browser implementation:

• Rich user experience

• Reduced load on server and network
Live Demo

• Samples of interactive web forms.
Automated Reasoning and Web Forms

Building a web form can be complicated.

- HTML/CSS for layout, colors, fonts, etc. is easy.
- JavaScript for detecting errors and computing implied values is hard, e.g. feature-oriented programming, configuration management.

**Error detection**: SAT solving specialized to the web form.

**Implied value computation**: theorem proving (TP) specialized to the web form.

A version of TP that tolerates inconsistency: paraconsistent TP.
 Plato: A Declarative Approach to Web Forms

Declarative approach

- Web programmer uses formal logic to describe acceptable web form data: *web form ontology*.
- Web programmer invokes a compiler (Plato) on the ontology to construct error-detection and implied-value computation code automatically.

Benefits

- Writing/maintaining an ontology is easier than JavaScript.
- Error-prone specialization of SAT/TP is performed automatically.
- Choice of paraconsistent TP can be left up to experts (compiler writers).
Live Demo 2

- Ontologies for earlier samples.
Outline

• Logical Foundations of Web Forms

• Plato’s Architecture

• Plato’s Compilation Algorithms

• Evaluation

• Related Work and Conclusions
Logical Foundations of Web Forms

Notation:

- $F$ is a set of web form fields, e.g. shipCity, shipState, shipZip, billCity, billState, billZip.
- $\Sigma$ is some character set, e.g. Latin-1 or UTF-8.

Definition (Payload): A web form payload is a subset of $F \times \Sigma^*$. Logically, a payload is a set of ground atoms $f(v)$ where $f$ in $F$ and $v$ in $\Sigma^*$.

Definition (Ontology): A web form ontology is a logical axiomatization of a set of payloads -- the acceptable payloads.

Today, we consider ontologies written in a fragment of first-order logic.
Shipping and Billing Addresses

Payload: \{shipCity(Chicago), shipState(Illinois)\}

Ontology: same \iff \forall x. \left( \land \begin{array}{l}
\text{shipCity}(x) \iff \text{billCity}(x) \\
\text{shipState}(x) \iff \text{billState}(x)
\end{array} \right)
Logical Foundations of Web Forms 2

• **Definition (Consistent):** A payload is *consistent* if it is a subset of an acceptable payload. All other payloads are *inconsistent*. A payload is *minimally inconsistent* if it is inconsistent and no subset is inconsistent.

• **Definition (Error):** There is one *error* in a payload for every minimally inconsistent payload contained within it.

• **Definition (Traditional Implication):** Suppose $P$ is a consistent payload for ontology $\Delta$. $P$ implies value $v$ for field $f$ if every consistent superset of $P$ includes $f(v)$.

  $$\Delta \vdash P \Rightarrow f(v)$$

• **Definition (Paraconsistent Implication):** Suppose $P$ is an inconsistent payload for ontology $\Delta$. $P$ implies value $v$ for field $f$ if there is some $P_0 \subset P$ that is consistent and implies $f(v)$.

  $$P \implies_{E} f(v)$$

• **Definition (Implied value):** Suppose $P$ is the payload comprised of the user-supplied key-value pairs on a web form. The form implies $f(v)$ exactly when $P$ paraconsistently implies $f(v)$. 
Shipping and Billing Addresses 2

- Payload: \{shipCity(Chicago), shipState(Illinois), same\}
- Error: none
- Implied values: billCity(Chicago) billState(Illinois)
- Consistent/inconsistent

- Add to payload: billCity(San Francisco)
- Error: \{shipCity(Chicago), same, billCity(San Francisco)\}
- Implied values under $\models_{\Delta}$
  <everything>
- Implied values under $\models_{\Delta_{E}}$
  billState(Illinois)
Monadic First-order Logic

A web form payload is a set of statements in monadic first-order logic. (All relations have at most 1 argument.)

\{\text{billCity(Chicago), billState(Illinois)}\}

Ontology language for today:
monadic, function-free, quantifier-free, equality-free, first-order logic (MON for short)

Syntax

- \(V\): a countable set of variables
- \(O\): a set of object constants (that includes \(\sum^*\))
- \(R\): a set of propositions
- \(P\): a set of relation constants

- \(\text{term } T ::= V \mid O\)

- \(\text{sentence } S ::= R \mid p(T) \mid S \land S \mid S \lor S \mid \neg S \mid S \Rightarrow S \mid S \Leftarrow S \mid S \leftrightarrow S\)

- free variables are implicitly universally quantified

Semantics: standard first-order semantics.
Computational Complexity of Implication

**Theorem**: Suppose $\Delta$ is in MON and $P$ is a finite set of ground atoms. The complexity of $\models_{E_0}$ is as follows.

- $\Pi_2$-hard and included in $\Pi_3$.
- $\Pi_1$-hard and $\Sigma_1$-hard and included in $\Pi_2$ if the number of variables in $\Delta$ is bounded by a constant.
- $\Pi_1$-hard if $\Delta$ is in clausal form and contains 1 variable.
- $\text{AC}^0$ (included in P) if $\Delta$ is of constant size.
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Compile Time vs. Run Time

Compile Time
- Compiler used by web programmer once.
- Web programmer will wait minutes.

Run Time
- Form used by many people.
- Each person generates many SAT/TP queries.
- People expect real-time results.
Web Form Skeleton

OnChange(field f)

1:   F := dependentFields(f)

// Compute errors       (some bookkeeping not shown)
2:   for each field g in F
3:      if hasvalue(g) then
4:         if error\_g() then paintred(g)

// Compute implied values
5:   for each field g in F
6:      if !(hasvalue(g)) then
7:         V := impliedValues\_g()
8:         setValues(g,V)
9:      if V ≠ ∅ then paintgreen(g)

Relies on two functions for each form field: error\_g and impliedValues\_g
Compiler Architecture

Traditional approach: write a SAT solver/a paraconsistent TP in JavaScript.

Drawback: the same ontology analysis is performed repeatedly but with different data.

Plato: construct JavaScript SAT/TP specialized to the ontology.

Benefits: (i) database compilation techniques well-known, (ii) (non-recursive) database queries are sentences in first-order logic.
Web Form Implication Compiler

**Definition (Web Form Implication Compiler):**

A web form ontology compiler is a function $\alpha$ that maps an ontology and a set of predicates to a set of first-order formulae.

$\alpha$ is a compiler if for any ontology $\Delta$, predicate set $F$, and predicate $f \in F$, there is a sentence $\varphi_f$ (impliedValues$_f$) in $\alpha[\Delta,F]$ such that for any payload $P$ and any object $v$

$$P \models^\Delta_E f(v) \text{ if and only if } \models_P \phi_f(v)$$

On the left, $P$ is treated with the open world assumption.
On the right, $P$ is treated with the closed world assumption.
Shipping and Billing Addresses 3

\[
\begin{array}{c|c}
\text{Shipping} & \text{Billing} \\
\hline
\text{City} & \text{City} \\
\text{State} & \text{State} \\
\end{array}
\]

\begin{itemize}
\item \text{Same} checkbox
\end{itemize}

Ontology: \[ \text{same} \equiv (\land \ \text{shipCity}(x) \Leftrightarrow \text{billCity}(x) \land \text{shipState}(x) \Leftrightarrow \text{billState}(x) ) \]

Compilation for fields \{\text{shipCity, shipState, same}\}:

\[ \phi_{\text{shipCity}}(x) \equiv \text{same} \land \text{billCity}(x) \]
\[ \phi_{\text{shipState}}(x) \equiv \text{same} \land \text{billState}(x) \]
\[ \phi_{\text{same}} \equiv \forall x. (\land \ \text{shipCity}(x) \Leftrightarrow \text{billCity}(x) \land \text{shipState}(x) \Leftrightarrow \text{billState}(x) ) \]

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• **Plato’s Compilation Algorithms**

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Overview

**implCompile**: Algorithm for constructing impliedValues\(_f\) for each form field \(f\).

**errCompile**: Algorithm for constructing error\(_f\) for each form field \(f\).

**compression**: Algorithm to compress ontology before compilation.
Traditional Implication via Database queries

Example 1.

\[ p(x) \Rightarrow q(x) \]
\[ q(x) \Rightarrow r(x) \]
\[ r(x) \Rightarrow s(x) \]

Database queries for implication.

\[ \phi_p(x) \equiv \bot \]
\[ \phi_q(x) \equiv p(x) \]
\[ \phi_r(x) \equiv p(x) \lor q(x) \]
\[ \phi_s(x) \equiv p(x) \lor q(x) \lor r(x) \]

Example 2.

\[ p(x) \Rightarrow q(x) \lor r(x) \]
\[ q(x) \Rightarrow s(x) \]
\[ r(x) \Rightarrow s(x) \]

Database queries for implication.

\[ \phi_p(x) \equiv \bot \]
\[ \phi_q(x) \equiv \bot \]
\[ \phi_r(x) \equiv \bot \]
\[ \phi_s(x) \equiv p(x) \lor q(x) \lor r(x) \]
Paraconsistent Implication via Database Queries

Example 3.

\[ p(x) \Rightarrow q(x) \]
\[ q(x) \Rightarrow r(x) \]
\[ r(x) \Rightarrow s(x) \]
\[ \neg p(a) \]

Database queries for paraconsistent implication.

\[ \phi_p(x) \equiv \bot \]
\[ \phi_q(x) \equiv p(x) \land \text{consistent}_{p(x)}(x) \]
\[ \phi_r(x) \equiv \left( \lor \begin{array}{c} p(x) \land \text{consistent}_{p(x)}(x) \\ q(x) \land \text{consistent}_{q(x)}(x) \end{array} \right) \]
\[ \phi_s(x) \equiv \left( \lor \begin{array}{c} p(x) \land \text{consistent}_{p(x)}(x) \\ q(x) \land \text{consistent}_{q(x)}(x) \\ r(x) \land \text{consistent}_{r(x)}(x) \end{array} \right) \]
Compilation Algorithm for Implied Values

Name: implCompile
Inputs: \( \Delta \), a web form ontology in MON.
\( F \), a set of web form fields (predicates).
Outputs: a set of first-order equivalences for computing paraconsistent implications.

Summary: (i) Compute definite Horn consequences, (ii) add consistency checks, (iii) apply predicate completion

1: \( \Delta := \text{resolutionClosure}[\Delta] \)
2: \( \Gamma_p := \emptyset \) for each predicate \( p \)
3: for each clause \( c \) in \( \Delta \)
4: for each contrapositive \( d \) of \( c \)
5: write \( d \) as \( p(x) \leftarrow \psi(x, y) \)
6: if \( p \in F \) and \( \neg \) does not occur in \( \psi(x, y) \)
7: \( \Gamma_p := \Gamma_p \cup \{ \psi(x, y) \wedge \text{consistent}_{\psi(x, y)}(x, y) \} \)
8: return \( \varphi_p = \lor \Gamma_p \) for each predicate \( p \)
Example

1. Resolution Closure

\[ \neg p(x) \lor q(x) \lor r(x) \]
\[ \neg p(x) \lor s(x) \lor r(x) \]
\[ \neg p(x) \lor q(x) \lor s(x) \]
\[ \neg p(x) \lor s(x) \]
\[ \neg q(x) \lor s(x) \]
\[ \neg r(x) \lor s(x) \]

\[ \phi_p(x) \equiv \bot \]
\[ \phi_q(x) \equiv \bot \]
\[ \phi_r(x) \equiv \bot \]

\[ \phi_s(x) \equiv \left( \bigvee p(x) \land \text{consistent}_{p(x)}(x) \right) \]
\[ \left( \bigvee q(x) \land \text{consistent}_{q(x)}(x) \right) \]
\[ \left( r(x) \land \text{consistent}_{r(x)}(x) \right) \]

2. Definite Horn Rules

\[ s(x) \Leftarrow p(x) \]
\[ s(x) \Leftarrow q(x) \]
\[ s(x) \Leftarrow r(x) \]

3. Consistency checks

and

Predicate completion
Soundness and Completeness

**Theorem**: implCompile is a web form implication compiler, *i.e.* for any ontology $\Delta$, predicate set $F$, and predicate $f \in F$, $\varphi_f$ in ImplCompile[$\Delta$,F] ensures that for any payload $P$ and any object $v$

\[ P \models^E_f (v) \text{ if and only if } \models_P \phi_f(v) \]
Consistency checks

Definition (consistent$_{\psi(x)}$): Suppose $\Delta$ is the web form ontology. consistent$_{\psi(x)}$(v) is true if and only if $\{\psi(v)\} \cup \Delta$ is consistent.

All of the consistency checks are of the form

$$\text{consistent}_{p_1(x_1) \land \ldots \land p_n(x_n)}(x_1, \ldots, x_n)$$

where the $p_i$s are web form fields.

The consistency check for $p_1(v_1) \land \ldots \land p_n(v_n)$ is true exactly when the payload $\{p_1(v_1), \ldots, p_n(v_n)\}$ is error-free.

Since the web form computes errors (before computing implied values), the consistency checks amount to simple subset checks of the errors.
Compilation Algorithm for Errors

Name: errCompile
Inputs: \( \Delta \), a web form ontology in MON.
\( F \), a set of web form fields (predicates).
Outputs: a set of first-order equivalences for computing (non-minimal) errors
Summary: (i) Compute anti-definite Horn consequences, (ii) apply predicate completion

1: \( \Delta := \text{resolutionClosure}[\Delta] \)
2: \( \Gamma_p := \emptyset \) for each predicate \( p \)
3: for each clause \( c \) in \( \Delta \)
4: for each contrapositive \( d \) of \( c \)
5: write \( d \) as \( \neg p(x) \Leftarrow \psi(x,y) \) // Negative literal
6: if \( p \in F \) and \( \neg \) does not occur in \( \psi(x,y) \)
7: \( \Gamma_p := \Gamma_p \cup \{\psi(x,y)\} \) // Dropped consistency check
8: return \( \varphi_p \equiv \lor \Gamma_p \) for each predicate \( p \)
Ontology Compression

Before compiling, Plato sometimes compresses the ontology with the hope of reducing the cost of the resolution closure.

Original Ontology:

\[ p(a) \land q(b) \land r(c) \]
\[ \lor \]
\[ p(b) \land q(d) \land r(e) \]
\[ p(d) \land q(c) \land r(a) \]

Compressed Ontology:

\[ p(x) \land q(y) \land r(z) \Rightarrow t(x, y, z) \]

where \( t \) is a new database table:

\[
\begin{array}{ccc}
  a & b & c \\
  b & d & e \\
  d & c & a \\
\end{array}
\]
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Evaluation of Ontology Language

Successes

• Built a handful of web form ontologies by hand.

• Wrote a translator from a language for configuration management problems (Configit) into MON.

Limitations

• String-level constraints, e.g. date field has the format mm/dd/yyyy, or password field must contain at least 6 characters.

• Structural constraints, e.g. each paper author has a first name, last name, and email; there can be arbitrarily many authors.
Evaluation of Compiler

**Analytical**: size of resolution closure (without compression)

Compiler

- Run-time is polynomial in the size of the resolution closure of the ontology.
- Output complexity is polynomial in the size of the resolution closure.

Code the compiler generates

- Size is polynomial in size of the resolution closure.
- Run-time is a single-exponential factor of the size of the resolution closure.

**Empirical**: impact of compression on resolution closure
Analytical Evaluation of Compiler

**Proposition:** The output complexity of the resolution closure for MON is EXPSPACE-hard and included in 2EXPSPACE. When the premises are in clausal form, contain exactly one variable, and include no object constants, the output complexity is EXPSPACE-complete.

**Proposition:** For any class of MON for which resolution’s output complexity is included in EXPSPACE, Plato produces time-optimal implementations of implied-value computation and error detection, unless P=NP.

**Corollary:** Plato produces time-optimal implementations for ontologies written in clausal form with one variable and no object constants, unless P=NP.
Empirical Evaluation of Compiler

- Ran resolution on compressed and uncompressed ontologies; 17 finished.
- Ontologies drawn from CLib configuration management problems.
Empirical Evaluation of Compiler

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- Ontologies drawn from CLib configuration management problems.

![Compression Ratio Chart]
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Related Work

Related work found in: web engineering, computer security, formal methods, programming languages, databases, artificial intelligence, configuration management.

Most work either disallows errors, does not support implication, or utilizes a version of paraconsistent implication that does not reduce to traditional implication without errors (values are only propagated in certain directions).

Exceptions:

- [Kassoff-Genesereth, 2007] used our version of paraconsistent implication but did not introduce compilation algorithms, complexity results, or compression.

- [Vlaeminck-Vennekens-Denecker, 2009] utilized omni-directional paraconsistent implication, but focused on approximate inference instead of compilation.

- [Hinrichs-Kao-Genesereth, 2009] focused on databases but did not leverage web form environment for consistency checks, include complexity results, or discuss compression.
Future Work

• Expanded ontology language and accompanying compilation.

• Expand to multiple ontologies for describing web forms, e.g. conflict resolution, layout, dynamic behavior.

• For web form front-ends to relational databases, extract web form ontology from database integrity constraints automatically.

• AJAX for checking constraints dependent on data in database that cannot be shipped to client.

• Expand from single web form to series of forms and their interaction with server.