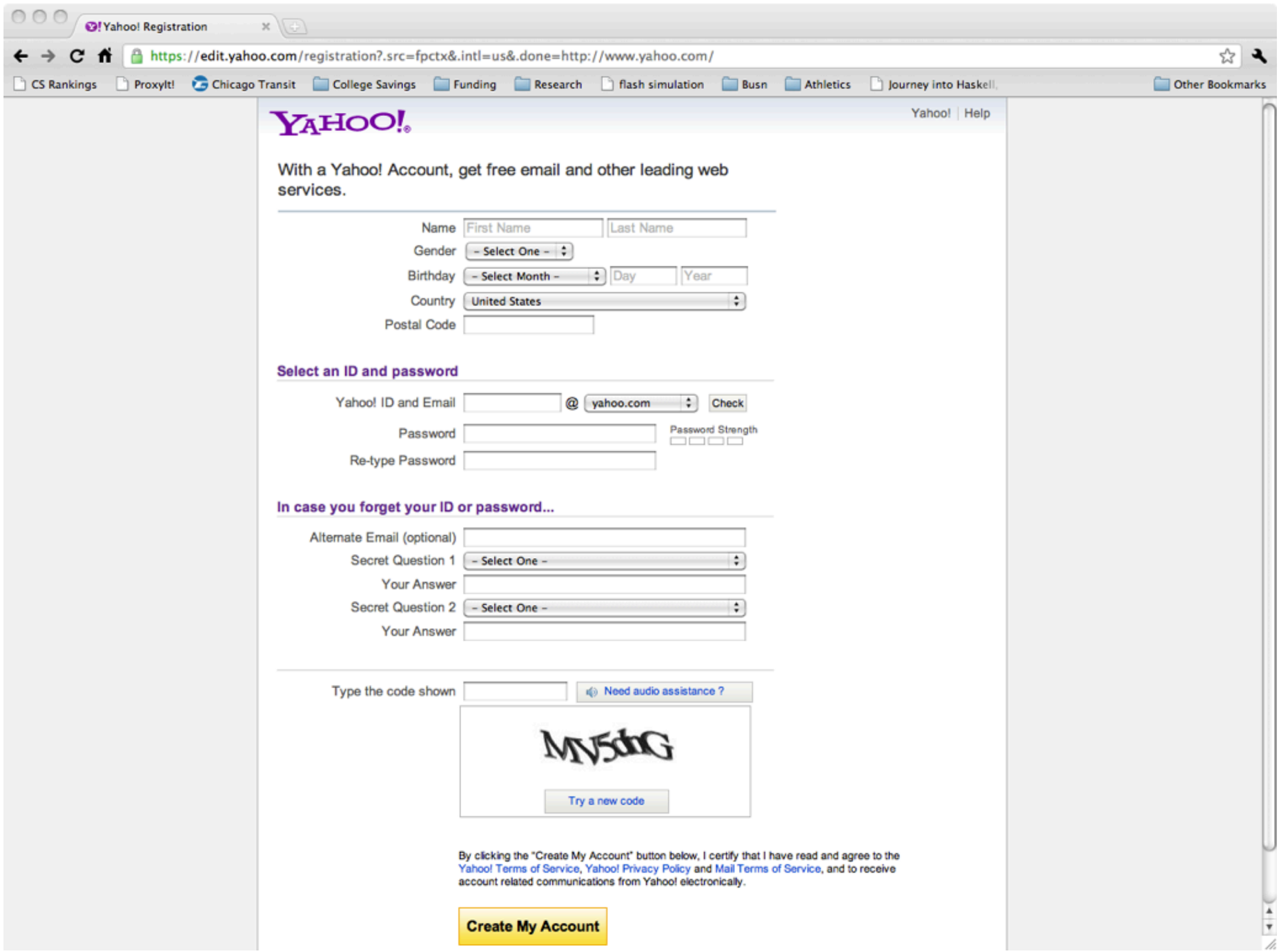

Plato: A Compiler for Web Forms

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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:

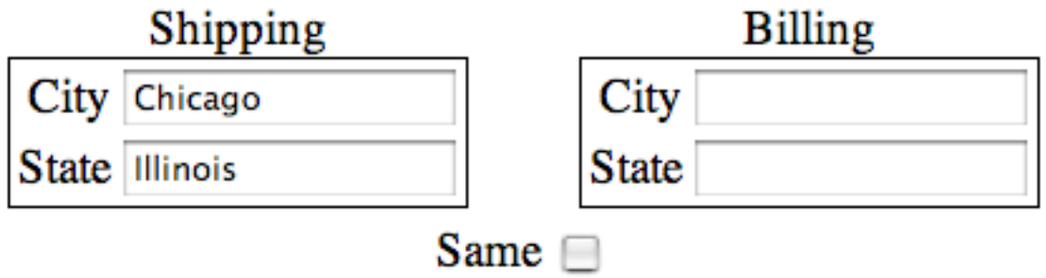
- F is a set of web form fields, e.g. shipCity, shipState, shipZip, billCity, billState, billZip.
- ∑ is some character set, e.g. Latin-1 or UTF-8.

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

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: $$same \Leftrightarrow \forall x. \left(\bigwedge \begin{array}{l} shipCity(x) \Leftrightarrow billCity(x) \\ shipState(x) \Leftrightarrow billState(x) \end{array} \right)$$

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 Δ. P implies value v for field f if every consistent superset of P includes f(v).

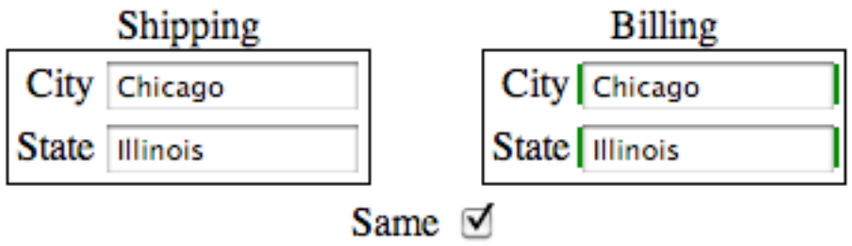
$$P \models^{\Delta} f(v)$$

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

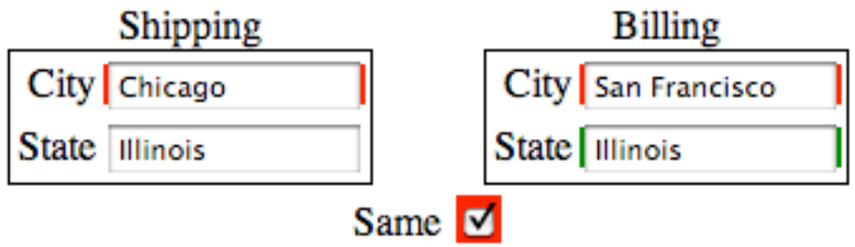
$$P \models^{\Delta}_{E} f(v)$$

- **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.)

{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
- term T ::= V | O
- sentence S ::= R | p(T) | S $\wedge$ S | S $\vee$ S | $\neg$ S | S $\Rightarrow$ S | S $\Leftarrow$ S | S $\Leftrightarrow$ S
- free variables are implicitly universally quantified

Semantics: standard first-order semantics.

Computational Complexity of Implication

Theorem: Suppose Δ is in MON and P is a finite set of ground atoms. The complexity of $\models^{\Delta}_{E}$ is as follows.

- $\prod_2$-hard and included in $\prod_3$.

- $\prod_1$-hard and $\sum_1$-hard and included in $\prod_2$ if the number of variables in Δ is bounded by a constant.

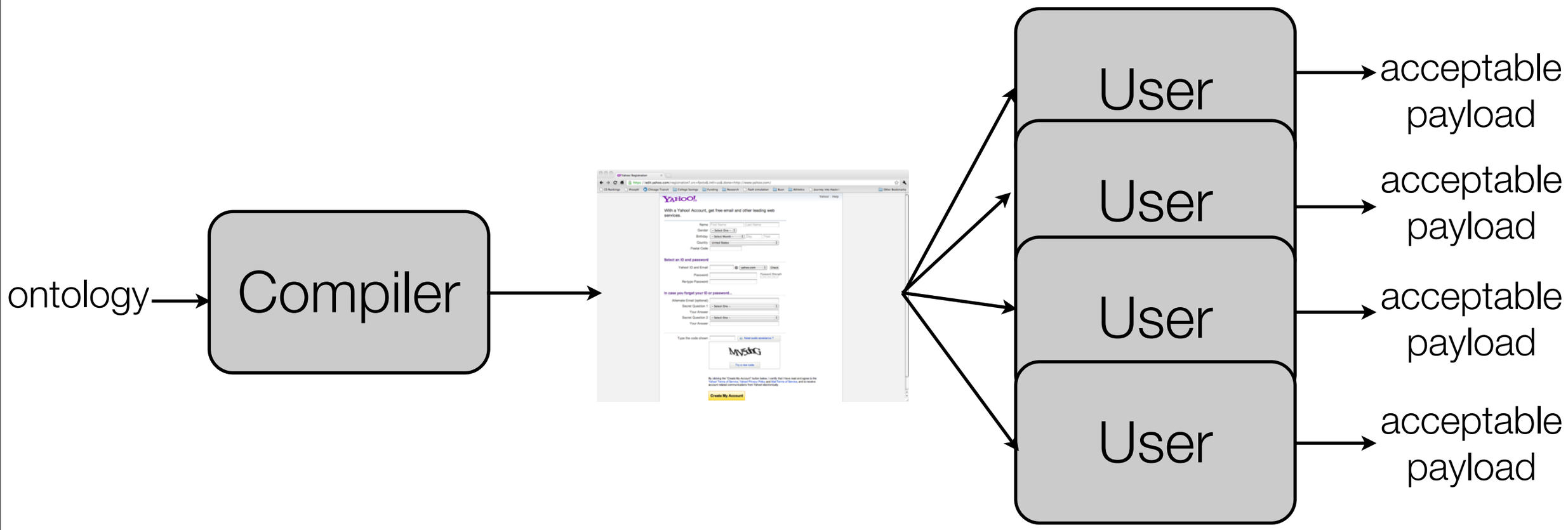
- $\prod_1$-hard if Δ is in clausal form and contains 1 variable.

- AC^0 (included in P) if Δ is of constant size.

Outline

- Logical Foundations of Web Forms
- **Plato's Architecture**
- Plato's Compilation Algorithms
- Evaluation
- Related Work and Conclusions

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):

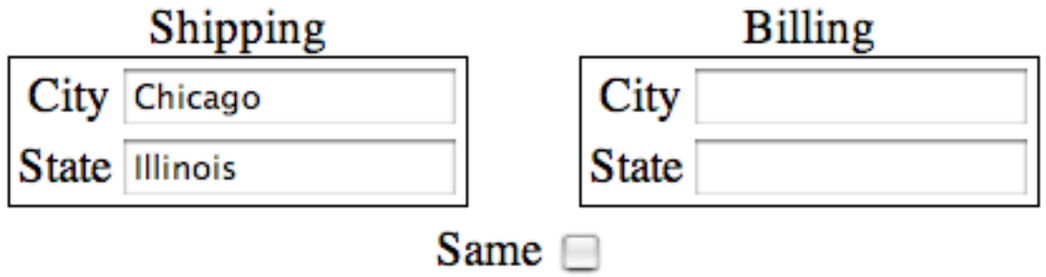
A web form ontology compiler is a function α that maps an ontology and a set of predicates to a set of first-order formulae.

α is a compiler if for any ontology Δ, predicate set F, and predicate f ∈ F, there is a sentence φ_f (impliedValues$_f$) in α[Δ,F] such that for any payload P and any object v

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

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



Ontology:

$$same \Leftrightarrow \left(\bigwedge \begin{array}{l} shipCity(x) \Leftrightarrow billCity(x) \\ shipState(x) \Leftrightarrow billState(x) \end{array} \right)$$

Compilation for fields {shipCity,shipState,same}:

$$\phi_{shipCity}(x) \equiv same \wedge billCity(x)$$

$$\phi_{shipState}(x) \equiv same \wedge billState(x)$$

$$\phi_{same} \equiv \forall x. \left(\bigwedge \begin{array}{l} shipCity(x) \Leftrightarrow billCity(x) \\ shipState(x) \Leftrightarrow billState(x) \end{array} \right)$$

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Overview

implCompile: Algorithm for constructing impliedValues_f for each form field f.

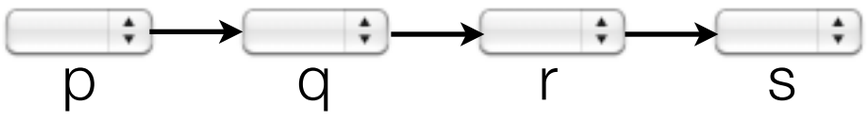
errCompile: Algorithm for constructing error_f for each form field f.

compression: Algorithm to compress ontology before compilation.

Traditional Implication via Database queries

Example 1.

$$p(x) \Rightarrow q(x)$$
$$q(x) \Rightarrow r(x)$$
$$r(x) \Rightarrow s(x)$$

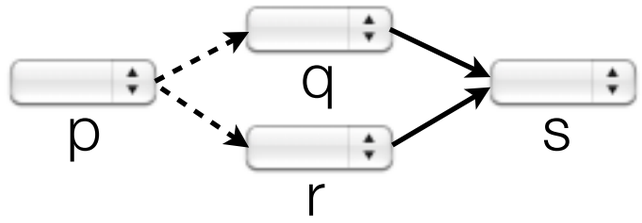


Database queries for implication.

$$\phi_p(x) \equiv \bot$$
$$\phi_q(x) \equiv p(x)$$
$$\phi_r(x) \equiv p(x) \vee q(x)$$
$$\phi_s(x) \equiv p(x) \vee q(x) \vee r(x)$$

Example 2.

$$p(x) \Rightarrow q(x) \vee r(x)$$
$$q(x) \Rightarrow s(x)$$
$$r(x) \Rightarrow s(x)$$



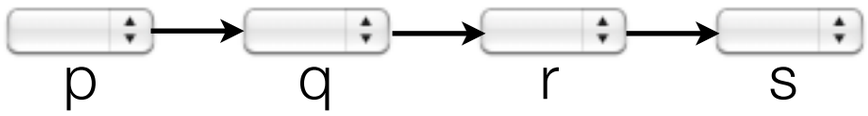
Database queries for implication.

$$\phi_p(x) \equiv \bot$$
$$\phi_q(x) \equiv \bot$$
$$\phi_r(x) \equiv \bot$$
$$\phi_s(x) \equiv p(x) \vee q(x) \vee r(x)$$

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.

$$\phi_p(x) \equiv \bot$$
$$\phi_q(x) \equiv p(x) \wedge consistent_{p(x)}(x)$$
$$\phi_r(x) \equiv \left(\bigvee \begin{array}{l} p(x) \wedge consistent_{p(x)}(x) \\ q(x) \wedge consistent_{q(x)}(x) \end{array} \right)$$
$$\phi_s(x) \equiv \left(\bigvee \begin{array}{l} p(x) \wedge consistent_{p(x)}(x) \\ q(x) \wedge consistent_{q(x)}(x) \\ r(x) \wedge consistent_{r(x)}(x) \end{array} \right)$$

Compilation Algorithm for Implied Values

Name: implCompile
Inputs: Δ, 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: $\Gamma_p := \varnothing$ **for each** predicate p
3: **for each** clause c in Δ
4: **for each** contrapositive d of c
5: write d as $p(x) \Leftarrow \psi(x,\mathbf{y})$
6: **if** $p \in F$ **and** ¬ does not occur in $\psi(x,\mathbf{y})$
7: $\Gamma_p := \Gamma_p \cup \{\psi(x,\mathbf{y}) \wedge \text{consistent}_{\psi(x,\mathbf{y})}(x,\mathbf{y})\}$
8: return $\varphi_p \equiv \bigvee \Gamma_p$ **for each** predicate p

Example

1. Resolution Closure

$$\neg p(x) \vee q(x) \vee r(x)$$
$$\neg p(x) \vee s(x) \vee r(x)$$
$$\neg p(x) \vee q(x) \vee s(x)$$
$$\neg p(x) \vee s(x)$$
$$\neg q(x) \vee s(x)$$
$$\neg r(x) \vee s(x)$$

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

$$\phi_p(x) \equiv \bot$$
$$\phi_q(x) \equiv \bot$$
$$\phi_r(x) \equiv \bot$$
$$\phi_s(x) \equiv \left(\bigvee \begin{array}{l} p(x) \wedge consistent_{p(x)}(x) \\ q(x) \wedge consistent_{q(x)}(x) \\ r(x) \wedge consistent_{r(x)}(x) \end{array} \right)$$

Soundness and Completeness

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

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

Consistency checks

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

All of the consistency checks are of the form

$$consistent_{p_1(x_1)\wedge\cdots\wedge p_n(x_n)}(x_1,\ldots,x_n)$$

where the p_is are web form fields.

The consistency check for $p_1(v_1) \wedge \ldots \wedge p_n(v_n)$ 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: Δ, 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: Δ := resolutionClosure[Δ]
2: $\Gamma_p := \varnothing$ **for each** predicate p
3: **for each** clause c in Δ
4: **for each** contrapositive d of c
5: write d as $\neg p(x) \Leftarrow \psi(x,\mathbf{y})$ // Negative literal
6: **if** $p \in F$ **and** ¬ does not occur in $\psi(x,\mathbf{y})$
7: $\Gamma_p := \Gamma_p \cup \{\psi(x,\mathbf{y})\}$ // Dropped consistency check
8: return $\varphi_p \equiv \bigvee \Gamma_p$ **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:

$$\bigvee \begin{array}{l} p(a) \wedge q(b) \wedge r(c) \\ p(b) \wedge q(d) \wedge r(e) \\ p(d) \wedge q(c) \wedge r(a) \end{array}$$

Compressed Ontology:

$$p(x) \wedge q(y) \wedge r(z) \Rightarrow t(x, y, z)$$

where *t* is a new database table:

a	b	c
b	d	e
d	c	a

Outline

- Logical Foundations of Web Forms
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- Plato's Compilation Algorithms
- **Evaluation**
- Related Work and Conclusions

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

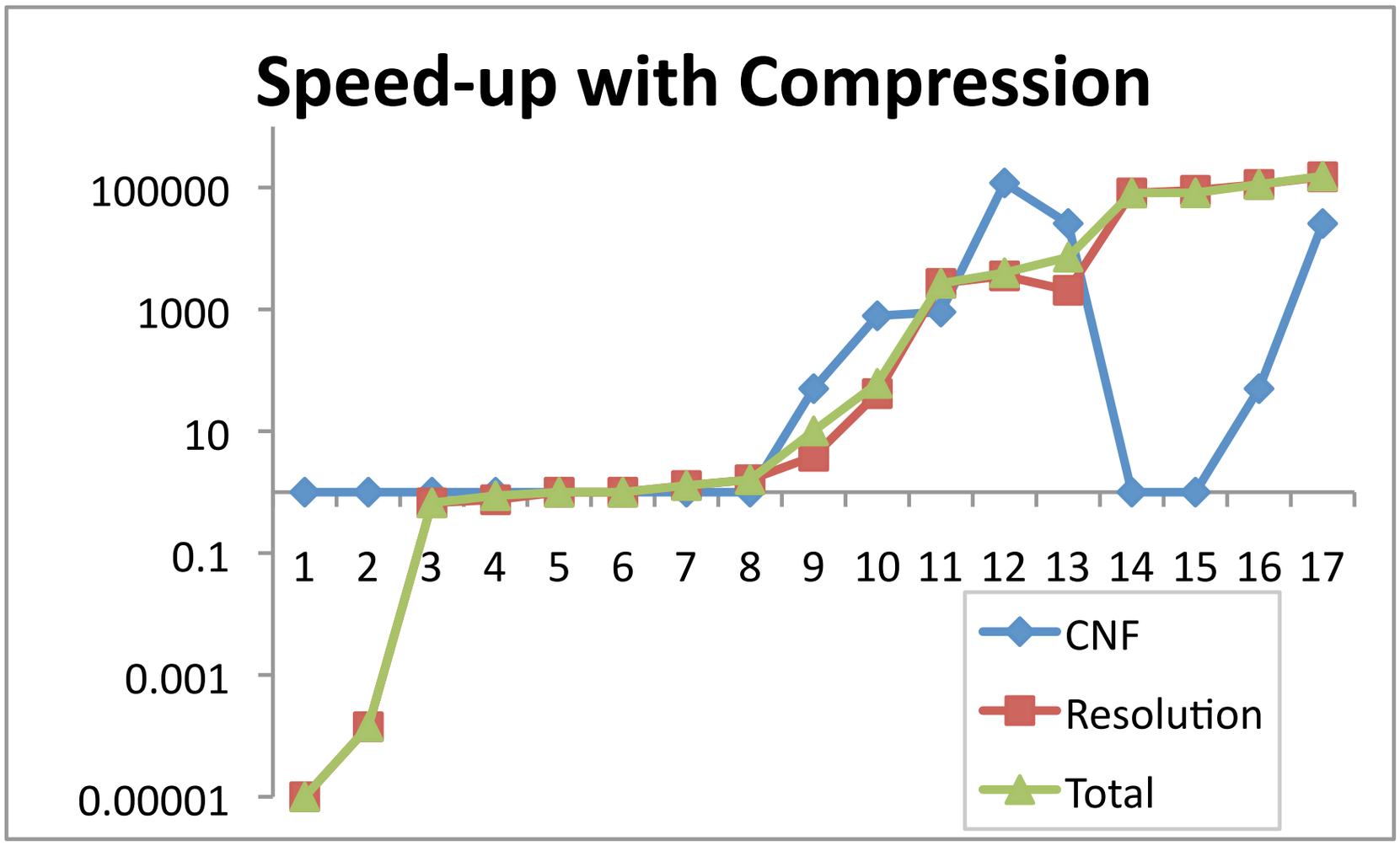
Proposition: The output complexity of the resolution closure for MON is EXPSPACE-hard and included in 2EXPSPACE. When the premises are in clausal form, contain exactly one variable, and include no object constants, the output complexity if EXPSPACE-complete.

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.



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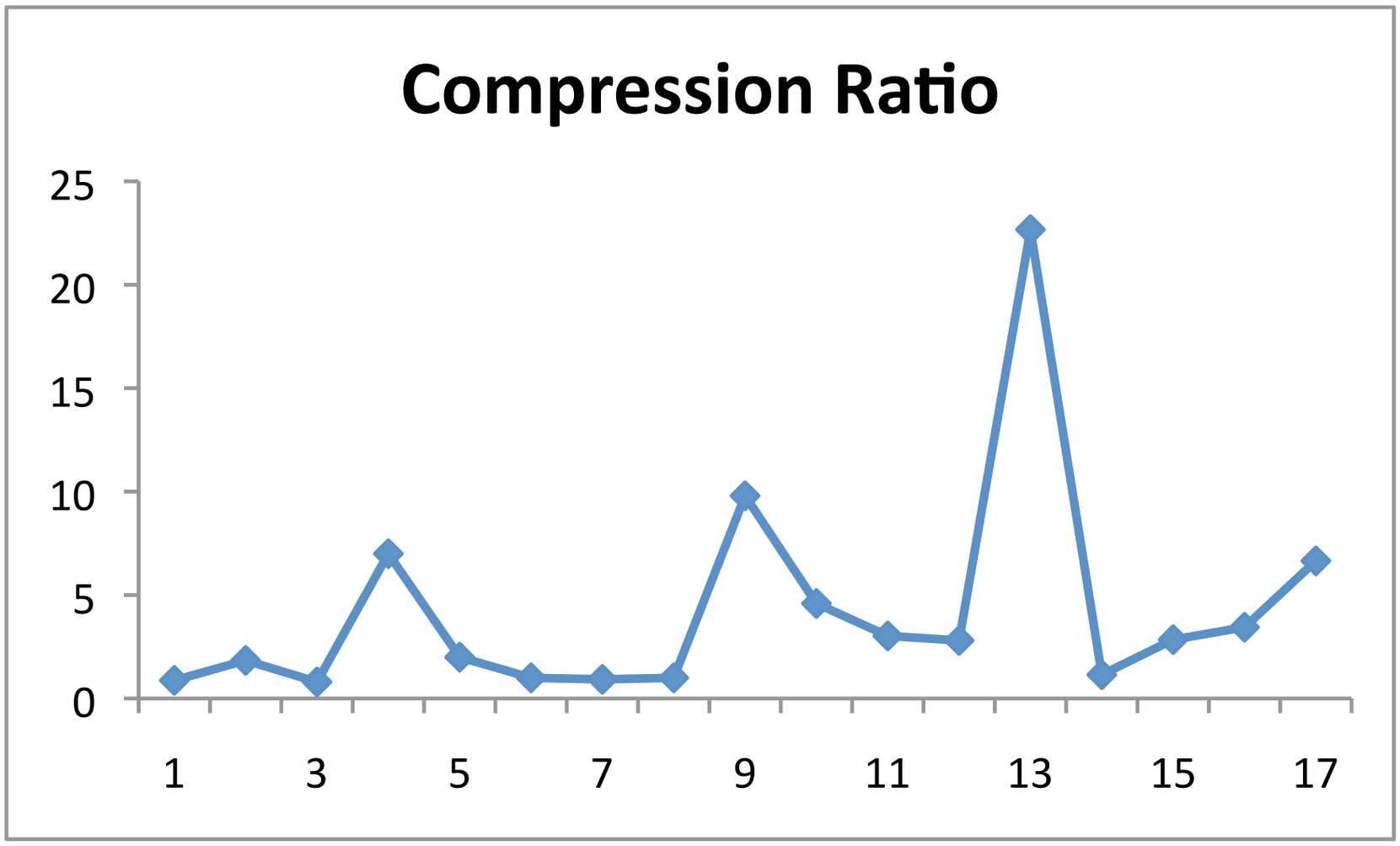

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Related Work

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 verison 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.