Combining Nonmonotonic Knowledge Bases with External Sources

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Recent Developments

- Traditional KR: monolithic, closed reasoning systems
- The World Wide Web
- Wealth of data / knowledge sources
- Distributed, open systems

Urgent Need

- access to external sources
- cope with heterogenity
- incompleteness
- recurrent data access
- dynamics

Issues:

- Semantics
- Algorithms, Implementations

Aim of this Talk

- Present some formalisms that combine possibly nonmonotonic knowledge bases with external sources
- Nonmonotonic formalisms have long tradition in Knowledge Representation and Reasoning
- **Focus:** recent work of KBS Group @ TU Vienna and colleagues
- **Observations:**
  - Principled issues
  - Research problems (theory, implementation)
  - On target for combining systems
  - . . . to new frontiers

Historic Background

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  $$friendly\_guy(X) \leftarrow most[likes](X)$$

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- IMPACT agent platform [Subrahmanian *et al.*, 2000]

  $$\mathbf{Do}\, notify(P, M) \leftarrow \mathbf{P}\, inform(P, M),\ in(P, db{:}getClients()),\ \mathrm{not}\ urgent(M)$$

- **But:** embryonic; limitations, drawbacks

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Around 2000: Emergence of Answer Set Programming

Answer Set Programming (ASP)

- Answer Set Programming (ASP) is a recent declarative problem solving approach.
- The term was coined by Lifschitz [1999,2002].
- Proposed by other people at about the same time, e.g. [Marek and Truszczyński, 1999], [Niemelä, 1999].
- It has roots in KR, logic programming, and nonmonotonic reasoning.
- At an abstract level, relates to SAT solving and CSP.
- Early book: [Baral, 2003]
- To date, ASP languages and systems are a major tool for building non-monotonic knowledge bases.

Roadmap

Logic Programs with Negation

- "War of Semantics" in Logic Programming (1980/90ies)

  Meaning of programs with negation "not" like the following:

$$
\begin{aligned}
&& man(joe). \\
single(X) &\leftarrow man(X), \mathrm{not}\, husband(X). \\
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  Intuitive models: $M_1 = \{man(joe), single(joe)\}$, $M_2 = \{man(joe), husband(joe)\}$.

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- Shift in LP: compute *Answer Sets (=models)*, not proofs!

ASP Paradigm

General idea: answer sets provide solutions!

$$\xrightarrow[\text{Instance } I]{\text{Problem}} \boxed{\begin{array}{c}\text{Encoding:}\\ \text{Program } P\end{array}} \longrightarrow \boxed{\text{ASP Solver}} \xrightarrow[\text{Solution(s)}]{\text{Model(s)}}$$

1. *Encode* problem instance I as a (non-monotonic) logic program P, such that solutions of I are represented by models of P
2. *Compute* some model M of P, using an ASP solver
3. *Extract* a solution for I from M.

Variant: Compute multiple models (for multiple / all solutions)

Often: Decompose I into *problem specification* and *data*

Note: Related to SAT Solving/CSP, but ASP offers special features (variables, supports transitivity)

Answer Set Solvers

DLV	`http://www.dbai.tuwien.ac.at/proj/dlv/` *
Smodels	`http://www.tcs.hut.fi/Software/smodels/` **
GnT	`http://www.tcs.hut.fi/Software/gnt/`
Cmodels	`http://www.cs.utexas.edu/users/tag/cmodels/`
ASSAT	`http://assat.cs.ust.hk/`
NoMore(++)	`http://www.cs.uni-potsdam.de/~linke/nomore/`
Platypus	`http://www.cs.uni-potsdam.de/platypus/`
clasp	`http://www.cs.uni-potsdam.de/clasp/`
XASP	`http://xsb.sourceforge.net`, distributed with XSB v2.6
aspps	`http://www.cs.engr.uky.edu/ai/aspps/`
ccalc	`http://www.cs.utexas.edu/users/tag/cc/`

* + extensions (DLVHEX, DVL^{DB}, DLT, ...)   ** + Smodels_cc

- Several provide a number of extensions to the language described here.
- ASP Solver competition: see LPNMR conference (2009 edition this week!);
- Benchmark platform: `http://asparagus.cs.uni-potsdam.de/`
- **Note:** clasp wins the *crafted instances* categories a) SAT+UNSAT and b) UNSAT instances of the SAT Competition 2009.

Answer Set Programs

Disjunctive Logic Program

A *(disjunctive) logic program* P is a (finite) set of rules of the form

$$a_1 \vee \cdots \vee a_l \leftarrow \ b_1, \ldots, b_m, \text{not} \ \ c_1, \ldots, \text{not} \ \ c_n$$

where all a_i, b_j, c_k are literals of the form p or $\neg p$, where p is a first-order atom over a (classical) first-order vocabulary.

- Standard ASP has no function symbols
- "$\neg$" is called strong negation (also written as "–")
- In *normal programs*, the rule head is a single literal ($l = 1$)

(Extended) Herbrand Base

HB_P is the set of all ground (variable-free) literals p and $\neg p$ with predicates and ground terms constructible from P.

Answer Sets

- Answer Sets are based on *3-valued Herbrand Interpretations (=consistent sets of ground literals $M \subseteq HB_P$)*, with incomplete information
- For programs without "$\neg$," they are also called "stable models" and viewed 2-valued, with complete information about the world.

Satisfaction

An interpretation $M \subseteq HB_P$ satisfies

- a ground rule $a_1 \vee \cdots \vee a_k \leftarrow b_1, \ldots, b_m, \text{not } c_1, \ldots, \text{not } c_n$, if $\{b_1, \ldots, b_m\} \subseteq M$ and $M \cap \{c_1, \ldots, c_n\} = \emptyset$ implies $M \cap \{a_1, \ldots, a_k\} \neq \emptyset$.
- a ground program P, if M satisfies each $r \in P$.
- a rule r, if M satisfies each $r' \in grnd(r)$, where $grnd(r)$ is the set of of all ground instances of r.
- a program P, if M satisfies $grnd(P) = \bigcup_{r \in P} grnd(r)$.

- For not*-free ("positive") programs*, an intuitive semantics are *minimal models*:

Minimal Model

An interpretation $M \subseteq HB_P$ is minimal model of P, if (i) M satisfies P and (ii) no $N \subset M$ satisfies P.

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- **Key idea for arbitrary programs:** elimination of not

Gelfond-Lifschitz (GL) reduct P^M

Given program P, remove from $grnd(P)$

1. every rule $a_1 \vee \cdots \vee a_k \leftarrow b_1, \ldots, b_m, \text{not } c_1, \ldots, \text{not } c_n$ where some c_i is in M, and
2. all literals $\text{not } c_j$ from the remaining rules.

Use M as an *assumption* on how negation finally evaluates.

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- For positive P, $P^M = P$, so the answer sets coincide with the minimal models
- Many equivalent definitions of answer sets / stable models exist [Lifschitz, 2008]

  E.g., Answer sets can be reconstructed in the logic of Here and There (*Equilibrium Logic* [Pearce, 2006])

Example

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\begin{aligned}
P = \{\ & person(joey);\\
& male(X) \vee female(X) \leftarrow person(X);\\
& bachelor(X) \leftarrow male(X), \mathrm{not}\, married(X)\ \}
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- Grounding of P

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P^{M_2} = \{\, & person(joey); \\
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- $M_2 = \{\mathit{person}(\mathit{joey}), \mathit{male}(\mathit{joey}), \mathit{married}(\mathit{joey})\}$ is not stable
- Further answer set: $M_3 = \{\mathit{person}(\mathit{joey}), \mathit{female}(\mathit{joey})\}$

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- Consider the program

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ASP Applications

See http://www.kr.tuwien.ac.at/projects/WASP/report.html

- information integration
- constraint satisfaction, configuration
- planning, routing
- diagnosis
- security analysis
- Semantic Web
- computer-aided verification
- biology / biomedicine
- knowledge management
- ...

ASP Showcase: http://www.kr.tuwien.ac.at/projects/WASP/showcase.html

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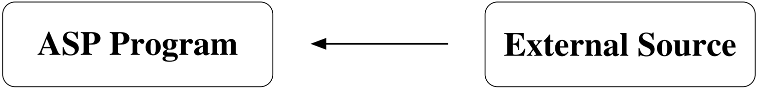
Scenarios



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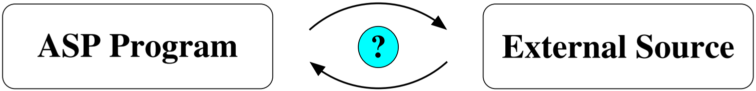

- Import of information: add facts
- Bidirectional information flow:
  - For ASP, a nontrivial aspect in general
  - Specifically, in case of recursion (minimality, stability)

Formalisms and Systems

- A variety of formalisms and systems has been proposed, e.g.,
  - GQLPs [E_ *et al.*, 1997], MLPs [Dao Tran *et al.*, 2009], DLP Functions [Janhunen *et al.*, 2007]
  - DLVEX [Calimeri *et al.*, 2007], HEX programs [E_ *et al.*, 2005], DLV^{DB} [Terracina *et al.*, 2008]
  - Nonmonotonic Multi-Context Systems [Brewka and E_, 2007]
- Related: Macros [Baral *et al.*, 2006], Templates [Ianni *et al.*, 2003], MWeb [Analyti *et al.*, 2008] etc.
- The proposals are different, yet not unrelated. Superficially,
  - MLPs can be viewed as special setting for HEX programs
  - MCSs are a kind of generalization of HEX programs
- **But:** relation not by intent; underlying philosophy/assumptions vary
- Systematic view helps

Two Major Aspects

world view	

Collection $KB = KB_1, \ldots, KB_n$ of knowledge bases / sources KB_i

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  - societal: *global state* $S = (S_1, \ldots, S_n)$ of local models S_i of KB_i; S is *explicitly* accessible $\Rightarrow$ global state preference

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Loosely speaking, *Nash equilibria* vs *Pareto-optimality*.

reduct world view	
local model globale state	

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- **program reduct**:

reduct / world view	GL-style
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- For ASP extensions, FLP retains minimality of models, but not GL.

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Other formalisms fit (e.g., dl-programs (ASP+DL): GL-style/local model)

HEX Programs

- Designed to meet needs of heterogenous data access on the Web
- Generalizes earlier *description logic programs* which provide ASP programs with query access to an OWL logic ontology.
- Allow to access sources of whatever type (no restriction; abstract modeling)
- **Features:**
  - Higher-Order atoms: variables for predicate names (syntactic sugar)
  - External atoms: access to external sources (increases expressivity)
- **Type:** FLP reduct / local model

An Example

$$
\begin{aligned}
invites(john, X) \vee skip(X) \leftarrow & X \neq john, \\
& \&DL\_Query[my\_ontology, relativeOf](john, X). \\
someInvited \leftarrow & invites(john, X). \\
\leftarrow & \text{not } someInvited. \\
\leftarrow & \&degs[invites](Min, Max), Max > 2.
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Example

Input: Data about *John*'s relatives (from an ontology)

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Example

Input: Data about *John*'s relatives (from an ontology)

Output: Possible picks for persons John might want to invite, according to some constraints (some evaluated externally)

$$\&DL\_Query[my\_ontology, relativeOf](john, X) \tag{1}$$

$$\&degs[invites](Min, Max) \tag{2}$$

External Atom

In general, an *external atom* a is of the form

$$\&g[Y_1, \ldots, Y_n](X_1, \ldots, X_m) \ , \tag{3}$$

where $Y_1, \ldots, Y_n$ and $X_1, \ldots, X_m$ are two lists of terms (called *input* and *output* lists, respectively), and $\&g$ is an external predicate name.

- External atoms may occur only in rule bodies; disregard $\neg$.
- Each $\&g$ is associated with an evaluation function $f_{\&g}$

Example

$\&DL\_Query$ corresponds to $f_{\&DL\_Query}$.

- Informally,

$$\&DL\_Query[my\_ontology, relativeOf](john, c)$$

  is true if $relativeOf(john, c)$ is provable in $my\_ontology$.

- This is formally captured via $f_{\&DL\_Query}$:

  For a given interpretation I,

$$I \models \&DL\_Query[my\_ontology, relativeOf](john, c)$$

  iff

$$f_{\&DL\_Query}(I, my\_ontology, relativeOf, john, c) = 1$$

Semantics of HEX programs P

- Higher order atoms $T_0(T_1, \ldots, T_n)$ are grounded to $t_0(t_1, \ldots, t_n)$.
- Herbrand base HB_P: all ground (ordinary, external) atoms.

Interpretations

An *interpretation* is any subset $I \subseteq HB_P$ containing only ordinary atoms.

Satisfaction and Answer Sets

As for ordinary ASP programs, where

- I satisfies any ground higher-order atom $a \in HB_P$ iff $a \in I$.
- I satisfies any ground $a = \&g[y_1, \ldots, y_n](x_1, \ldots, x_m)$ iff $f_{\&g}(I, y_1, \ldots, y_n, x_1, \ldots, x_m) = 1$, where $f_{\&g}$ is a *fixed* $(n+m+1)$-ary function with range $\{0, 1\}$ for $\&g$ ($I \subseteq HB_P$, x_i, y_j ground terms).

For answer sets, use FLP reduct instead of GL reduct:

- Interpretation I is an answer set of P, iff I is a minimal model of fP^I.

Choice of FLP Reduct

Proposition

Every answer set of a HEX-program P is a minimal model of P.

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This fails for the GL-reduct P^I in place of fP^I.

Example

$$p(a) \leftarrow \text{not } \&neg[p](a)$$

Suppose $f_{\&neg}(I, p)$ computes the complement of p (negation)

- Under GL-reduct, both $\emptyset$ and $\{p\}$ are answer sets
- Under FLP-reduct, only $\emptyset$ is an answer set

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- Under FLP-reduct, only $\emptyset$ is an answer set

However, GL and FLP reduct are equivalent for monotonic external atoms.

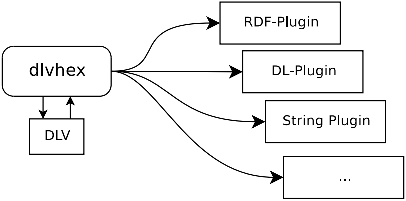
Theorem

Suppose in P all external atoms α are monotonic, i.e., for each $\alpha' \in grnd(\alpha)$, $I \subseteq J \subseteq HB_P \wedge I \models \alpha'$ implies $J \models \alpha'$. Then $ans_{GL}(P) = ans_{FLP}(P)$.

Implementation

- Algorithms: reduction to ordinary ASP, generalization of techniques
- System prototype: dlvhex

  `http://www.kr.tuwien.ac.at/research/systems/dlvhex/`



- Flexible, modular architecture
- External atoms are realized by plugins (loaded at run-time)
- Pool of plugins available
- New plugins can be defined by the user

Applications

- Fuzzy ASP [Nieuwenborgh *et al.*, 2007a], [Heymans and Toma, 2008]
- Planning with Sensing [Nieuwenborgh *et al.*, 2007b]
- Biomedical ontologies [Hoehndorf *et al.*, 2007]
- Haplotype inference
- Web querying (SPARQL) [Polleres, 2007]
- Data integration
- Trust management [Schindlauer, 2006]
- Process management in building construction [Rybenko, 2009]

Modular Nonmonotonic Logic Programs (MLPs)

- Goal: Structured programming
- In ASP, different directions:
  - Programming in the large: compositional operators

    E.g., DLP-functions [Janhunen *et al.*, 2007]
  - Programming in the small: abstraction and scoping

    E.g., Generalized Quantifiers [E_ *et al.*, 1997], Macros [Baral *et al.*, 2006], Templates [Ianni *et al.*, 2003]
- **Our aim**: Provide module ("procedure") concept as in ordinary programming
  - realize libraries, code reuse
- MLPs: look like special HEX programs, but are different
- **Type:** FLP reduct / global state

Program Modules

Conventional programming:

- Definition:

  proc p(var x, y: int): int
  begin
  ...
  end p;

- Use: $x := p(y, z)$;

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- Use: $x := p(y, z);$

Nonmonotonic LP:

- Definition:

  Module $m = (P[q_1, q_2], R)$, where
  - P is a module name
  - q_1, q_2 are predicate names
  - R is a set of rules

- Use: $p(X) \leftarrow P[r, s].even$

Modular Logic Program

A *modular (nonmonotonic) logic program* (MLP) $\mathbf{P} = (m_1, \ldots, m_n)$, $n \geq 1$, consists of modules $m_i = (P_i[\vec{q}_i], R_i)$ where at least one m_i has void $\vec{q}_i$.

Rule bodies may contain *module atoms* $P[p_1, \ldots, p_k].o(t_1, \ldots, t_l)$, where $p_1, \ldots, p_k$ are predicate names and $o(t_1, \ldots, t_l)$ is an ordinary atom.

Semantics (Essentials)

- For module $m_i = (P_i[\vec{q}_i]; R_i)$, each interpretation S of $\vec{q}_i$ yields an instance of m_i, named $P_i[S]$.
- An interpretation $\mathbf{M} = (M_i/S \mid P_i[S])$ of $\mathbf{P}$ consists of ordinary interpretations M_i/S for all instances $P_i[S]$ of all modules m_i in $\mathbf{P}$.
  (*global state*)
- In $P_i[S]$,
  - ordinary $o(\vec{t})$ evaluates to $o(\vec{t}) \in M_i/S$;
  - $P_j[\vec{p}_j].o(\vec{t})$ evaluates to $o(\vec{t}) \in M_j/S'$ where S' *takes the value of* $\vec{p}$ *in* M_i/S (*call by value*).
- For answer sets, extend notion of minimal model and FLP reduct to $\mathbf{P}$ (componentwise, i.e., for all $P_i[S]$).

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- For answer sets, extend notion of minimal model and FLP reduct to $\mathbf{P}$ (componentwise, i.e., for all $P_i[S]$).

Natural Question

Can't each module be simply cast to a HEX program
(module atom = external atom)?

- Difference: Global minimization (essential for loops, recursion)

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Example

$$P_1: \quad a \leftarrow P_2[\,].b \qquad P_2: \quad b \leftarrow P_1[\,].a$$

- Answer set: $\mathbf{M}_1 = (\emptyset, \emptyset)$
- Non-minimal model: $\mathbf{M}_2 = (\{a\}, \{b\})$
- As HEX programs, P_1 and P_2 have also $\mathbf{M}_2$ as answer set.

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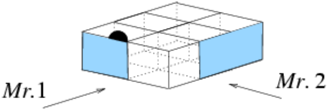
- As HEX programs, P_1 and P_2 have also $\mathbf{M}_2$ as answer set.

- Note: MLPs exclude infinite recursion.
- Still the semantics is very expressive (2-NEXP$^{\mathrm{NP}}$ vs. NEXP$^{\mathrm{NP}}$).
- Preliminary GQLPs had no recursion, used GL reduct and local models
- Refined MLP semantics takes *relevant* module calls into account.

Multi-Context Systems



- In AI, McCarthy [1987] first investigated contexts.
- Intuitively, a multi-context system describes the information available in several contexts (to people / agents/ databases etc)
- The Trento School (Giunchiglia, Serafini et al.):

  Information flow via *bridge rules* between contexts

  - Heterogeneous MCS [Giunchiglia and Serafini, 1994]
  - Nonmonotonic bridge rules [Roelofsen and Serafini, 2005]
  - Extension to Contextual Default Logic [Brewka *et al.*, 2007]
- Nonmonotonic Multi-Context Systems [Brewka and E_, 2007]:
  - abstract “logics” (description / modal / default logics, ASP, . . .)

Nonmonotonic Multi-Context Systems (MCSs)

Multi-Context System

Formally, a Multi-Context System

$$M = (C_1, \ldots, C_n)$$

consists of contexts

$$C_i = (L_i, kb_i, br_i),\ i \in \{1, \ldots, n\},$$

where

- each L_i is a "logic,"
- each kb_i is a knowledge base in L_i, and
- each br_i is a set of L_i-bridge rules over M's logics.

Logic

A *logic* L is a tuple $L = (\mathbf{KB}_L, \mathbf{BS}_L, \mathbf{ACC}_L)$, where

- $\mathbf{KB}_L$ is a set of well-formed knowledge bases, each being a set (of formulas)
- $\mathbf{BS}_L$ is a set of possible belief sets, each being a set (of formulas)
- $\mathbf{ACC}_L : \mathbf{KB}_L \rightarrow 2^{\mathbf{BS}_L}$ assigns each KB a set of acceptable belief sets

Thus, logic L caters for multiple extensions of a knowledge base.

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Bridge Rules

A L_i-bridge rule over logics $L_1, \ldots, L_n$, $1 \leq i \leq n$, is of the form

$$s \leftarrow (r_1 : p_1), \ldots, (r_j : p_j), \textbf{not } (r_{j+1} : p_{j+1}), \ldots, \textbf{not } (r_m : p_m)$$

where $kb \cup \{s\} \in \mathbf{KB}_i$ for each $kb \in \mathbf{KB}_i$, each $r_k \in \{1, \ldots, n\}$, and each p_k is in some belief set of L_{r_k}.

Note: Such rules are akin to rules of normal logic programs!

Example

Suppose a MCS $M = (C_1, C_2)$ has contexts that express the individual views of a paper by the two authors.

- C_1:
  - L_1 = Classical Logic
  - $kb_1 = \{\, unhappy \supset revision \,\}$
  - $br_1 = \{\, unhappy \leftarrow (2 : work) \,\}$
- C_2:
  - L_2 = Reiter's Default Logic
  - $kb_2 = \{\, good : accepted/accepted \,\}$
  - $br_2 = \{\, work \leftarrow (1 : revision),$
    $good \leftarrow$ **not** $(1 : unhappy) \,\}$

Equilibrium Semantics

Belief State

A *belief state* is a sequence $S = (S_1, \ldots, S_n)$ of belief sets S_i in L_i

Applicable Bridge Rules

For $M = (C_1, \ldots, C_n)$ and belief state $S = (S_1, \ldots, S_n)$, the bridge rule

$$s \leftarrow (r_1 : p_1), \ldots, (r_j : p_j), \textbf{not } (r_{j+1} : p_{j+1}), \ldots, \textbf{not } (r_m : p_m)$$

is *applicable in* S iff (1) $p_i \in S_{r_i}$, for $1 \leq i \leq j$, and (2) $p_k \notin S_{r_k}$, for $j < k \leq m$.

Equilibrium

A belief state $S = (S_1, \ldots, S_n)$ of M is an equilibrium iff for all $i = 1, \ldots, n$,

$$S_i \in \mathbf{ACC}_i(kb_i \cup \{head(r) \mid r \in br_i \text{ is applicable in } S\}) \,.$$

Note: Interpretable as Nash-equilibrium of an n-player game

Example (ctd)

Reconsider $M = (C_1, C_2)$:

- $kb_1 = \{\, unhappy \supset revision \,\}$ (Classical Logic)
- $br_1 = \{\, unhappy \leftarrow (2 : work) \,\}$

- $kb_2 = \{\, good : accepted / accepted \,\}$ (Default Logic)
- $br_2 = \{\, work \leftarrow (1 : revision),$
  $good \leftarrow \textbf{not}\ (1 : unhappy) \,\}$

M has two equilibria:

- $E_1 = (Th(\{unhappy, revision\}), Th(\{work\}))$ and
- $E_2 = (Th(\{unhappy \supset revision\}), Th(\{good, accepted\}))$

Groundedness

- Problem: Equilibria admit self-justifying beliefs (loops)

Example (ctd)

Intuitively, E_1 is ungrounded, since *unhappy* has a cyclic justification:

- Accept *unhappy* in C_1, since *work* is accepted in C_2, since *revision* is accepted in C_1, since *unhappy* is accepted in C_1.

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- "Groundedness" may be achieved if the logics L_i have *monotonic cores* ML_i (kb_i has a single, monotonically growing belief set).
- $M = (C_1, \ldots, C_n)$ has a unique minimal equilibrium wrt. the ML_i.
- Reduce M, given a belief state S, to $M^S = (C_1^S, \ldots, C_n^S)$ in the ML_i's.
- For bridge rules, a GL-style reduct br_i^S is used.

MCS vs. HEX programs

- MCSs take a global state view, HEX programs a local model view
- Modeling $M = (C_1, \ldots, C_n)$
  - as a collection $(P_1, \ldots, P_n)$ of HEX programs is not feasible.
  - in a *single* HEX program P_M is feasible (under conditions).

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- **Idea**: Model formulas $(r_l : p_l)$ in bridge rules by external atoms $\&con\_r_l[\,](a_{p_l})$ being true iff p_l is in belief set S_{r_l} (a_{p_l} is a name for p_l).

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For the same kb_i, C_i might have multiple possible belief sets;

How to ensure that different atoms $\&con\_r_l[\,](\cdot)$ model access to the *same* belief set?

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> How to ensure that different atoms $\&con\_r_l[\,](\cdot)$ model access to the *same* belief set?

- Possible, if each belief set S_i is uniquely identified by a (small) subset (*kernel*, exists in many logics)

Ongoing Work at KBS

- *Modular* HEX *programs*:
  - Formalisms and reasoning techniques
  - Algorithms (local and distributed)
  - Reasoning framework (e.g., host for distributed SPARQL)
- *Inconsistency Management for Knowledge Integration Systems*:
  - A general formalism and basic methods for inconsistency management in MCSs.
  - Algorithms for their practical realization.
  - Applications; e.g., Argumentation Context Systems (ACSs) [Brewka and E_, 2009]
    - integrate individual Dung-style argumentation frameworks $\mathcal{A}_1, \ldots, \mathcal{A}_n$
    - *mediator* M_i configures $\mathcal{A}_i$ with input from $\mathcal{A}_j$'s and manages arising inconsistency.

Theory, proofs of concepts, prototypes

Conclusion

Summary

- Need for knowledge bases with access to external sources
- Several ASP extensions address this, featuring non-monotonicty
- Different types and settings (environment view, reduct)
- An interesting area of research

Issues

- Formalisms and semantics: incompleteness, approximation
- Algorithms and methods: heterogenity, distribution, optimization (e.g., source access)
- Implementation: reasoning platforms
- Applications

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Example MLP: Checking Even

$\mathbf{P} = (m_1, m_2, m_3)$, where $m_1 = (P_1, R_1)$, $m_2 = (P_2[q_2], R_2)$, $m_3 = (P_3[q_3], R_3)$.

$$R_1 = \{q(a).\quad q(b).\quad ok \leftarrow P_2[q].even.\}$$

$$R_2 = \left\{ \begin{array}{rcl} q_2'(X) \vee q_2'(Y) & \leftarrow & q_2(X), q_2(Y), \\ & & X \neq Y. \\ skip_2 & \leftarrow & q_2(X), \text{not } q_2'(X). \\ even & \leftarrow & \text{not } skip_2. \\ even & \leftarrow & skip_2, P_3[q_2'].odd. \end{array} \right\}$$

$$R_3 = \left\{ \begin{array}{rcl} q_3'(X) \vee q_3'(Y) & \leftarrow & q_3(X), q_3(Y), \\ & & X \neq Y. \\ skip_3 & \leftarrow & q_3(X), \text{not } q_3'(X). \\ odd & \leftarrow & skip_3, P_2[q_3'].even. \end{array} \right\}$$

$main()$:

$n := |q|$
if $even(n)$ **then return** ok

$even(n)$:

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Example MLP: Checking Even

$\mathbf{P} = (m_1, m_2, m_3)$, where $m_1 = (P_1, R_1)$, $m_2 = (P_2[q_2], R_2)$, $m_3 = (P_3[q_3], R_3)$.

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Checking Even (ctd)

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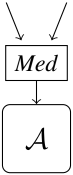
$\mathbf{M}$
$M_1/\emptyset : \{ok, q(a), q(b)\}$
$M_2/\{q_2(a), q_2(b)\} : \left\{ \begin{array}{l} even, skip_2, \\ q_2(a), q_2(b), q_2'(b) \end{array} \right\}$
$M_2/\emptyset : \{even\}$
$\vdots$
$M_3/\{q_3(b)\} : \{odd, skip_3, q_3(b)\}$
$\vdots$

Argumentation Context Systems (ACSs)

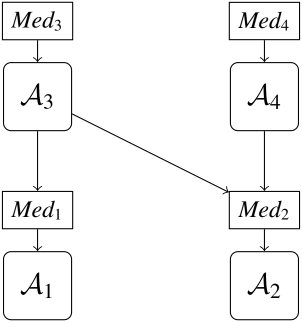
- Nonmonotonic MCS neglect two important aspects:
  1. What if information provided by different contexts is conflicting?
  2. What if a context does not only add information?
- ACSs provide an answer to these questions.
- Focus on a particular type of local reasoners:
  Dung-style argumentation frameworks [Dung, 1995]
- Goals are achieved by introducing mediators.

Argumentation Modules



- An argumentation module $\mathcal{M}$ is equipped with a mediator Med which can “listen" to other modules and “talk" to the argumentation framework $\mathcal{A}$ of $\mathcal{M}$.
- Med sets an *argumentation context* for $\mathcal{A}$ (semantics, reasoning mode, etc) expressed in a description language, depending on local and imported information, using bridge rules
- inconsistencies in the setting are treated using a parametric *inconsisteny handling method*

Example ACS



An argumentation context system.