Answer Set Programming with External Sources

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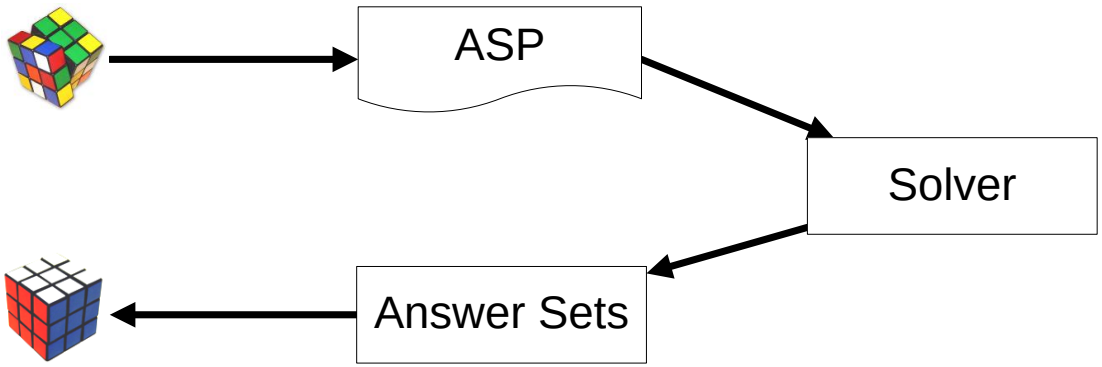
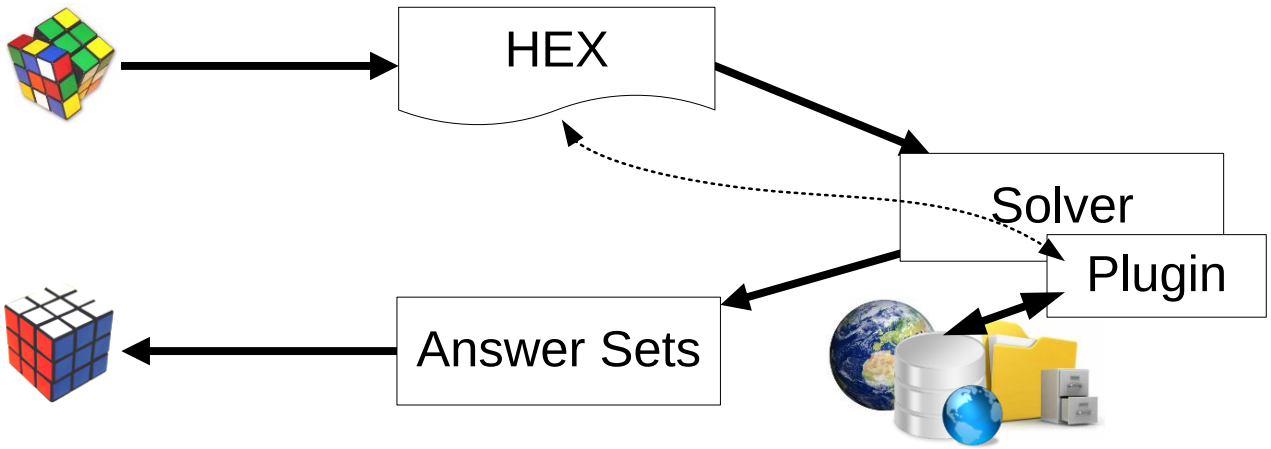
ASP-Programs



Rules:

$$a_1 \vee \cdots \vee a_n \leftarrow b_1, \ldots, b_m, \text{not } b_{m+1}, \ldots, \text{not } b_n,$$

HEX-Programs



Rules:

$$a_1 \vee \cdots \vee a_n \leftarrow b_1, \ldots, b_m, \text{not } b_{m+1}, \ldots, \text{not } b_n,$$

External atom:

$$\&p[q_1, \ldots, q_k](t_1, \ldots, t_l)$$

$$\&p[q_1, \ldots, q_k](t_1, \ldots, t_l) = true \Leftrightarrow f_{\&p}(\mathbf{A}, q_1, \ldots, q_k, t_1, \ldots, t_l) = 1$$

HEX-Programs

&rdf

$$addr(\texttt{http://.../data1.rdf}).$$
$$addr(\texttt{http://.../data2.rdf}).$$
$$bel(X,Y) \leftarrow addr(U), \&rdf[U](X,Y,Z).$$

HEX-Programs

&rdf

$$addr(\texttt{http://.../data1.rdf}).$$
$$addr(\texttt{http://.../data2.rdf}).$$
$$bel(X,Y) \leftarrow addr(U), \&rdf[U](X,Y,Z).$$

&diff

$$\begin{aligned} dom(X) &\leftarrow \#int(X). \\ nsel(X) &\leftarrow dom(X), \&diff[dom, sel](X). \\ sel(X) &\leftarrow dom(X), \&diff[dom, nsel](X). \\ &\leftarrow sel(X1), sel(X2), sel(X3), X1 \neq X2, X1 \neq X3, X2 \neq X3. \end{aligned}$$

Evaluation

Translation

Π:

$$p(c_1).\ dom(c_1).\ dom(c_2).\ dom(c_3).$$
$$p(X) \leftarrow dom(X), \&empty[p](X).$$

$\hat{\Pi}$:

$$p(c_1).\ dom(c_1).\ dom(c_2).\ dom(c_3).$$
$$p(X) \leftarrow dom(X), e_{\&empty[p]}(X).$$
$$e_{\&empty[p]}(X) \vee \neg e_{\&empty[p]}(X) \leftarrow dom(X).$$

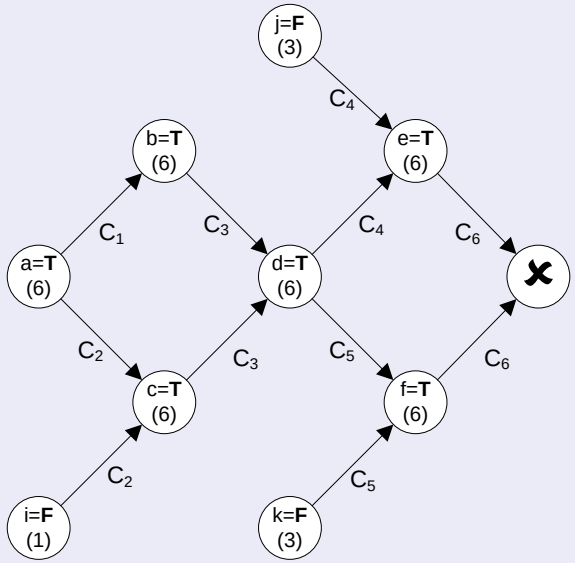
8 candidates, e.g.:

$\{\mathbf{T}p(c_1), \mathbf{T}p(c_2), \mathbf{T}dom(c_1), \mathbf{T}dom(c_2), \mathbf{T}dom(c_3),$
$\mathbf{F}e_{\&empty[p]}(c_1), \mathbf{T}e_{\&empty[p]}(c_2), \mathbf{F}e_{\&empty[p]}(c_3)\}$

Evaluation

Conflict-driven SAT/ASP Solving

$$\begin{aligned}\mathcal{C} \quad = \quad & \{C_1 : \{\neg a, b\}, C_2 : \{\neg a, c, i\}, C_3 : \{\neg b, \neg c, d\}, C_4 : \{\neg d, e, j\}, C_5 : \{\neg d, e, k\}, \\ & C_6 : \{\neg e, \neg f\}, C_7 : \{a, g, \neg l\}, C_8 : \{a, h\}, C_9 : \{\neg g, \neg h, \neg m\}\}\end{aligned}$$



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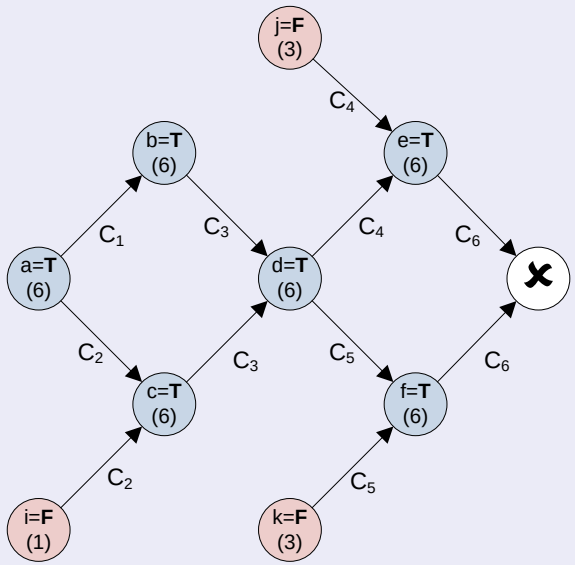

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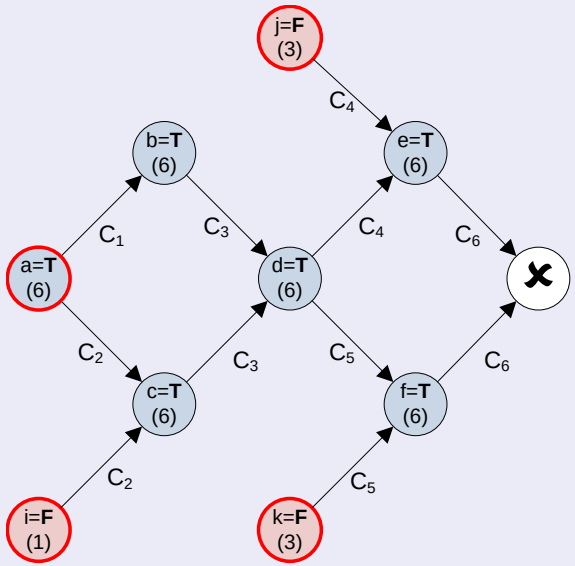

Evaluation

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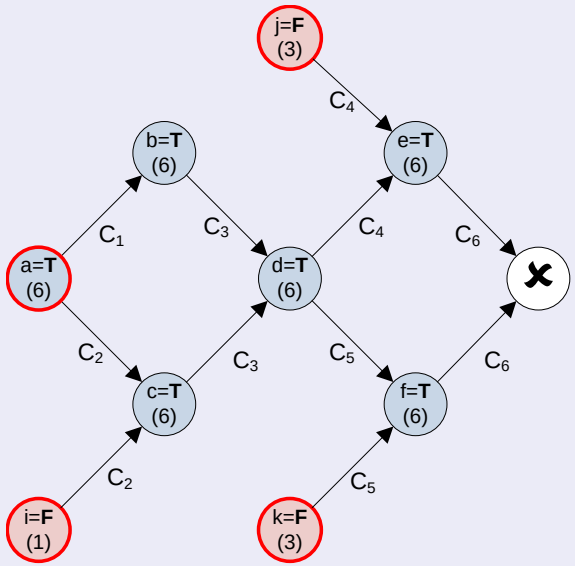
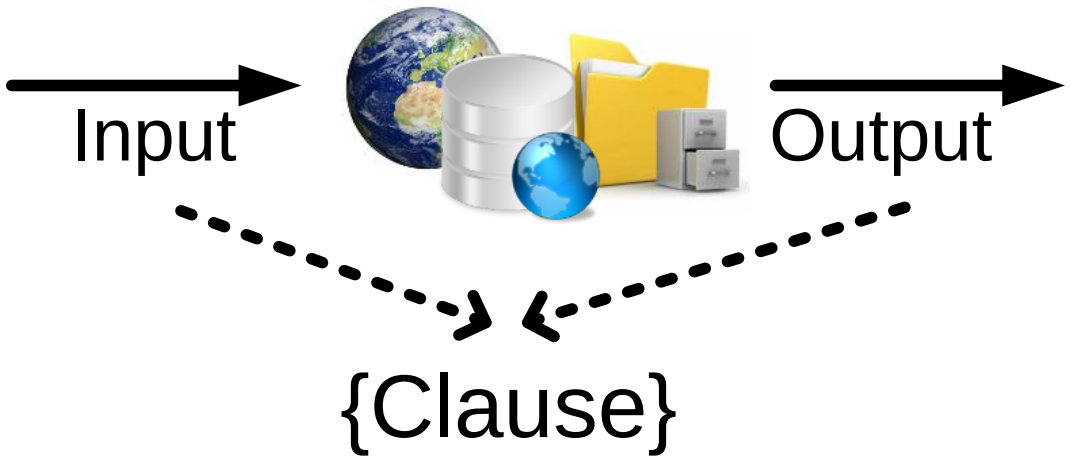
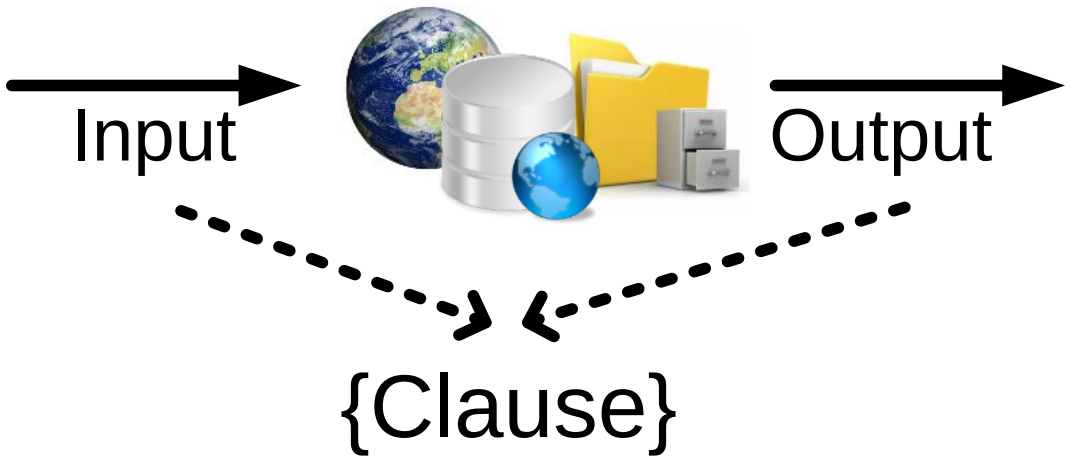


Evaluation: External Behavior Learning (EBL)



Evaluation: External Behavior Learning (EBL)



General Case

$\&diff[p,q](X), ext(p,\mathbf{A}) = \{a,b\}, ext(q,\mathbf{A}) = \{a,c\}$

$p(a) \wedge p(b) \wedge \neg p(c) \wedge q(a) \wedge \neg q(b) \wedge q(c) \rightarrow e_{\&diff[p,q]}(b)$

$\Rightarrow \{\neg p(a), \neg p(b), p(c), \neg q(a), q(b), \neg q(c), e_{\&diff[p,q]}(b)\}$

Evaluation: External Behavior Learning (EBL)

Monotonicity

$\&diff[p,q](X), ext(p,\mathbf{A}) = \{a,b\}, ext(q,\mathbf{A}) = \{a,c\}$
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Functionality

$\&concat[ab,c](X)$
$\Rightarrow \{\neg e_{\&concat[ab,c]}(abc), \neg e_{\&concat[ab,c]}(ab)\}$

Evaluation: External Behavior Learning (EBL)

Monotonicity

$\&diff[p,q](X), ext(p,\mathbf{A}) = \{a,b\}, ext(q,\mathbf{A}) = \{a,c\}$
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Evaluation: External Behavior Learning (EBL)

Monotonicity

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$\Rightarrow \{\neg p(a), \neg p(b), \neg q(a), q(b), \neg q(c), e_{\&diff[p,q]}(b)\}$

Functionality

$\&concat[ab,c](X)$
$\Rightarrow \{\neg e_{\&concat[ab,c]}(abc), \neg e_{\&concat[ab,c]}(ab)\}$

Evaluation: Minimality Check

Example

Π:

$$dom(a).\ dom(b).$$
$$p(a) \leftarrow dom(a), \&g[p](a).$$
$$p(b) \leftarrow dom(b), \&g[p](b).$$

$\&g$:

$$\emptyset \to \{b\}, \{a\} \to \{a\}, \{b\} \to \emptyset, \{a,b\} \to \{a,b\}$$

$\mathbf{A} = \{\mathbf{T}dom(a), \mathbf{T}dom(b), \mathbf{T}p(a)\} \models \Pi$

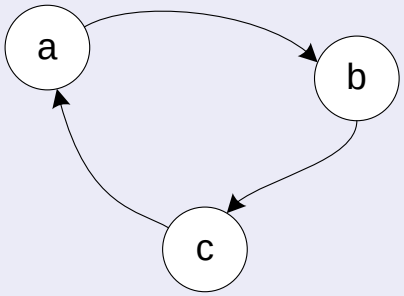
But FLP-reduct $f\Pi^{\mathbf{A}} = \{r \in \Pi \mid \mathbf{A} \models B(r)\}$:

$$dom(a).\ dom(b).$$
$$p(a) \leftarrow dom(a), \&g[p](a).$$

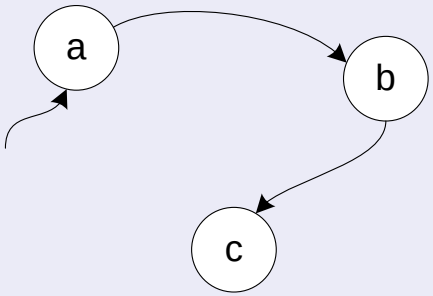
$\mathbf{A}' = \{\mathbf{T}dom(a), \mathbf{T}dom(b)\} \models f\Pi^{\mathbf{A}}$

Evaluation: Minimality Check

Unfounded Sets



$$b \leftarrow a.$$
$$c \leftarrow b.$$
$$a \leftarrow c.$$

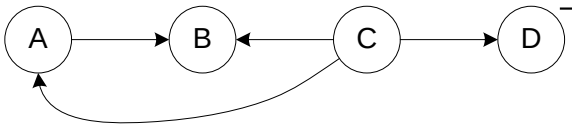


$$b \leftarrow a.$$
$$c \leftarrow b.$$
$$a.$$

Benchmarks

	n	5	6	7	8	9	10	11	12	13	...	20
all AS	explicit	10.9	94.3	—	—	—	—	—	—	—	—	—
	+EBL	4.3	34.8	266.1	—	—	—	—	—	—	—	—
	UFS	0.2	0.3	0.8	1.8	4.5	11.9	32.4	92.1	273.9	—	—
	+EBL	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.8	1.2	· · ·	11.1
first AS	explicit	0.7	4.3	26.1	163.1	—	—	—	—	—	—	—
	+EBL	0.8	4.9	31.1	192.0	—	—	—	—	—	—	—
	UFS	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	· · ·	0.5
	+EBL	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	· · ·	0.3

Figure: Set Partitioning



n	all AS		first AS	
	explicit	UFS	explicit	UFS
5	1.47	1.13	0.70	0.62
6	4.57	2.90	1.52	1.27
7	19.99	10.50	3.64	2.77
8	80.63	39.01	9.46	6.94
9	142.95	80.66	30.12	20.97
10	240.46	122.81	107.14	63.50

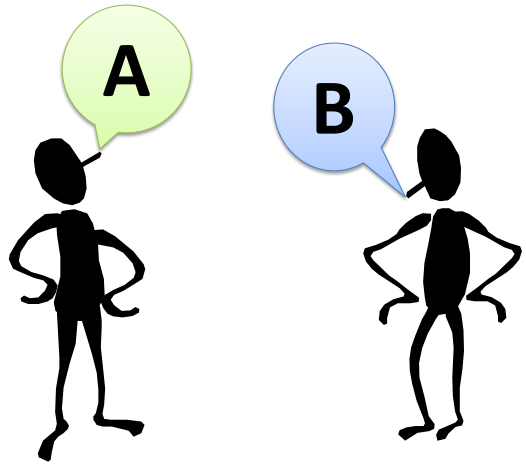
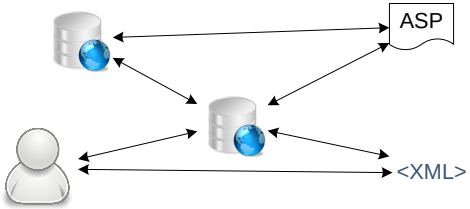
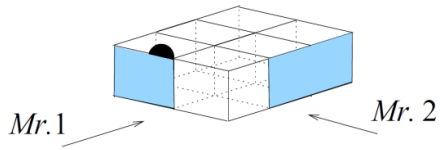


Figure: Argumentation

Benchmarks



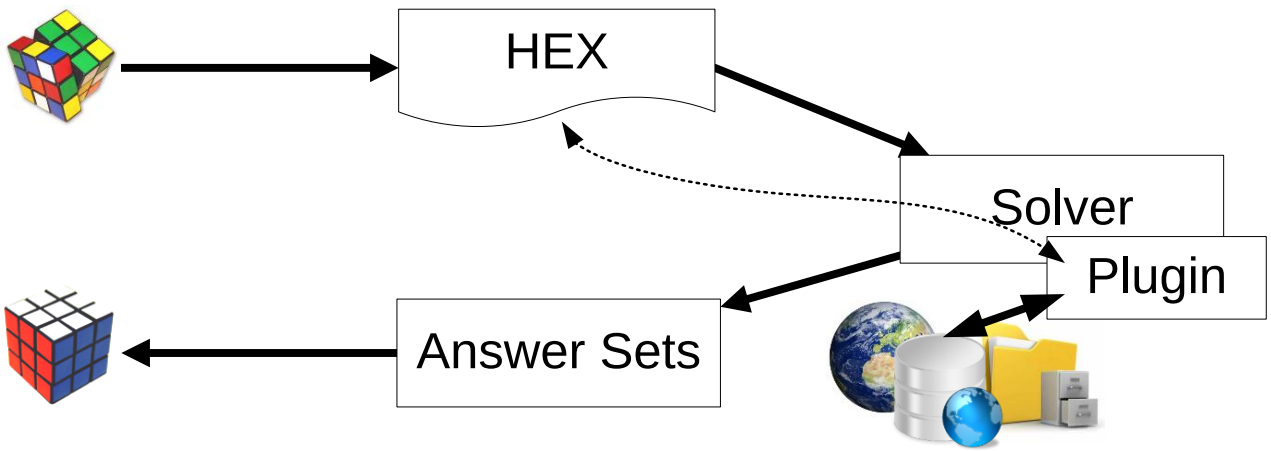
n	explicit		UFS check		
	plain	+EBL	plain	+EBL	+UFL
3	8.61	4.68	7.31	2.44	0.50
4	86.55	48.53	80.31	25.98	1.89
5	188.05	142.61	188.10	94.45	4.62
6	209.34	155.81	207.14	152.32	14.39
7	263.98	227.99	264.00	218.94	49.42
8	293.64	209.41	286.38	189.86	124.23
9	—	281.98	—	260.01	190.56
10	—	274.76	—	247.67	219.83



n	all AS					first AS				
	explicit		UFS			explicit		UFS		
	plain	+EBL	plain	+EBL	+UFL	plain	+EBL	plain	+EBL	+UFL
3	9.08	6.11	6.29	2.77	0.85	4.01	2.53	3.41	1.31	0.57
4	89.71	36.28	80.81	12.63	5.27	53.59	16.99	49.56	6.09	1.07
5	270.10	234.98	268.90	174.23	18.87	208.62	93.29	224.01	32.85	3.90
6	236.02	203.13	235.55	179.24	65.49	201.84	200.06	201.24	166.04	28.34
7	276.94	241.27	267.82	231.08	208.47	241.09	78.72	240.72	66.56	16.41
8	286.61	153.41	282.96	116.89	69.69	201.10	108.29	210.61	103.11	30.98
9	—	208.92	—	191.46	175.26	240.75	112.08	229.14	76.56	44.73
10	—	—	—	289.87	289.95	—	125.18	—	75.24	27.05

Figure: MCSs

HEX-Programs



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