Abduction in meta-reasoning

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NII

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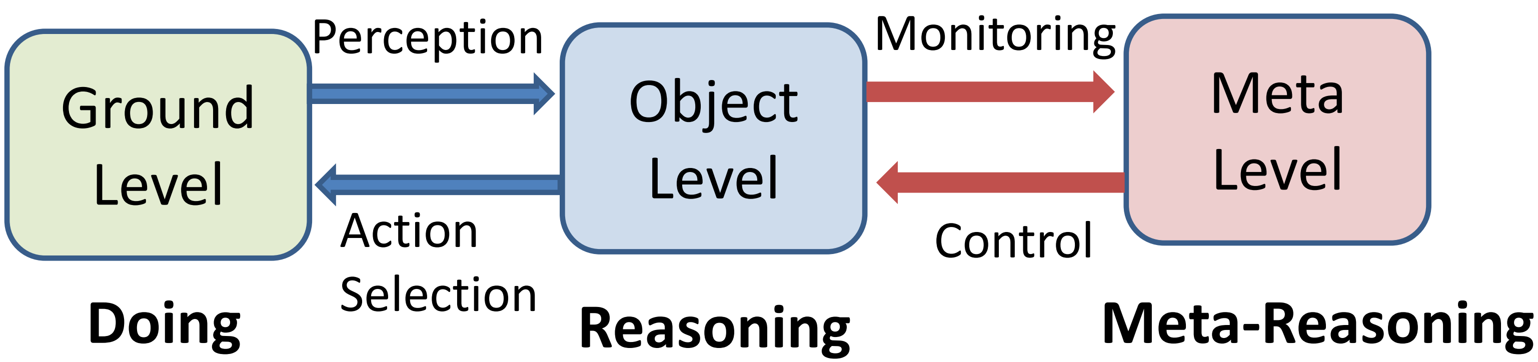
Meta-reasoning



- Stuart Russel and others
  - The meta-level control of the reasoning process itself.
  - The introspective monitoring of the reasoning process at the object level.
- Kowalski initiated meta-programming in logic programming [Bowen & Kowalski, 82].

Kowalski's meta interpreter

solve(A & B) $\leftarrow$ solve(A) & solve(B).

solve($\neg$A) $\leftarrow$ $\neg$solve(A).

…

solve(A) $\leftarrow$ clause(A$\leftarrow$B) & solve(B).

- In general, any **inference rule** can be expressed in such a meta-rule, e.g.,

  solve(A$\leftarrow$B) $\leftarrow$ solve(A$\leftarrow$C) & solve(C$\leftarrow$B).

  solve($\neg$A) $\leftarrow$ solve(B$\leftarrow$A) & solve($\neg$B).

- All constructs with **meta-predicates** "solve", "clause", or "demo" are atoms, yet their arguments take complex formulas.
- Those meta-level axioms are used for *deduction* only.

Abductive inference

- Abduction augments sufficient conditions missing in the premises (i.e., background knowledge) to enable a derivation (i.e., proof) of the given observation.
- This inference *fills the gap* in a proof of the observation from the premises.
- Inferred sufficient conditions are called **hypotheses** or **explanations**.
- Theoretically, a hypothesis can be any formula, e.g., a set (conjunction) of atoms/literals/rules, but abductive procedures usually treat a set of atoms.

Meta-level abduction

- Abduction is performed on meta-level axioms.
- For example, from

 solve(A) ← clause(A←B) & solve(B).

and

 solve(A) & solve(B),

we can abduce

 clause(A←B).

In this example, we can realize *rule abduction*.

But this is an ordinary abduction since it abduce atoms.

Implementation

- Although the idea of meta-level abduction is simple, its implementation requires an abductive procedure for first-order full clausal theories.
- Currently SOLAR [Nabeshima *et al*., 2003, 2010] (a consequence-finder based on SOL calculus [Inoue, 1992]) is only such a state-of-the-art procedure.

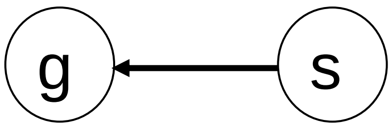
A simple logic of causality

- To express relations between events, we use **causal chains**.
- Causality can be represented in first-order predicate logic.
- Two meta-predicates:
  1. **connected(X,Y)**: X is *directly caused by* Y.
  2. **caused(X,Y)**: There is a *causal chain* from Y to X.

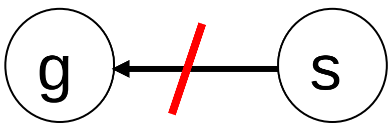
- Basic axioms:

$$\text{caused}(X,Y) \leftarrow \text{connected}(X,Y).$$
$$\text{caused}(X,Y) \leftarrow \text{connected}(X,Z) \wedge \text{caused}(Z,Y).$$

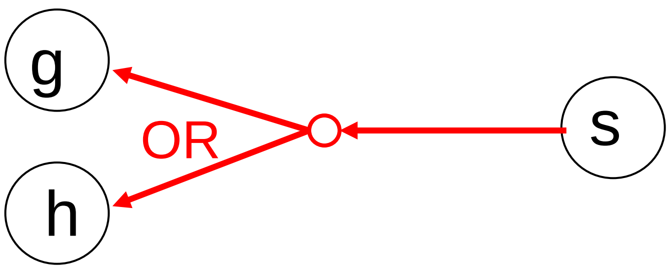
Representing logical connectives



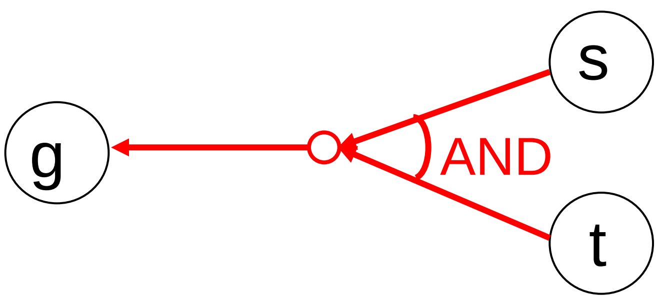
connected(g, s).



¬*connected(g, s).*



connected(g, s) ∨ *connected(h, s)*



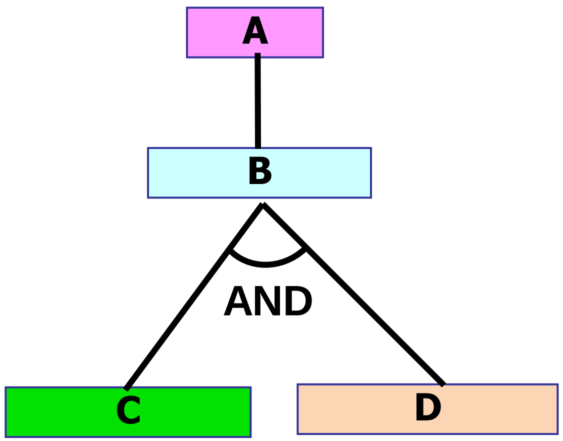
connected(g, s) ∨ *connected(g, t)*

Object and meta level representation

- **<u>Object domain (object level)</u>**

  A ← B.

  B ← C ∧ D.

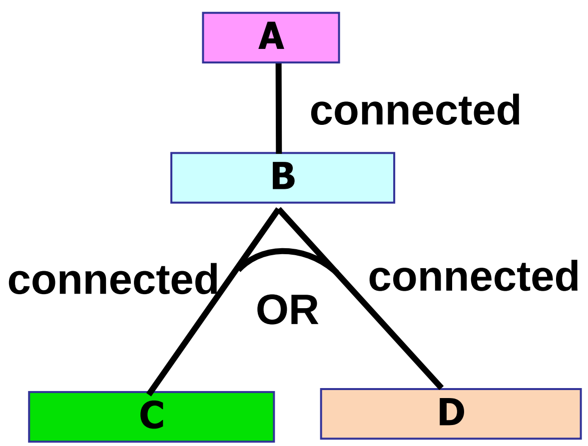


- Each *rule* in the object level is represented as a *fact* in the meta level.
- Each *literal* in the object level is represented as a *term* in the meta level.

- **<u>Causal relations (meta level)</u>**

  connected(A, B).

  connected(B, C) v **connected(B, D).**

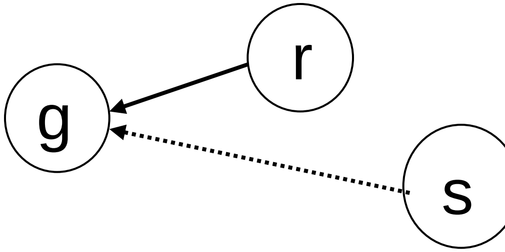


- *Rule abduction* in the object level is realized by abducing literals of the form *connected(_,_)* at the meta level.

Formalizing rule abduction

- *g*: a **goal,** *s*: an **input,** *r*: a (hidden) node

B: *connected(g, r).*
$\leftarrow$ *connected(g, s).*



That is, *g* is directly caused by *r*, but *g* is ***not*** directly caused by *s*.

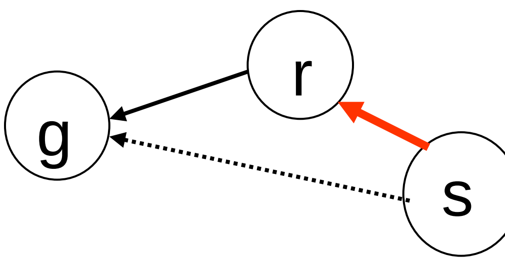
- *g* is not directly caused by *s*, but we know that there is a causal chain to *g* from *s*.

This is given by an observation:

G: *caused(g, s).*

- SOLAR computes a hypothesis

H: *connected(r, s),*



given the abducibles {*connected(_,_)*}.

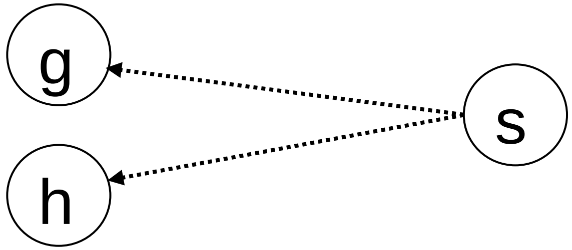
Node introduction = Predicate invention

- *g, h* : goal nodes, *s*: an input node.

B: $\leftarrow$ *connected(g, s).*

$\leftarrow$ *connected(h, s).*

That is, there are no direct causal relations from *s* to *g* and from *h* to *s*, but there are causal chains as the observations:

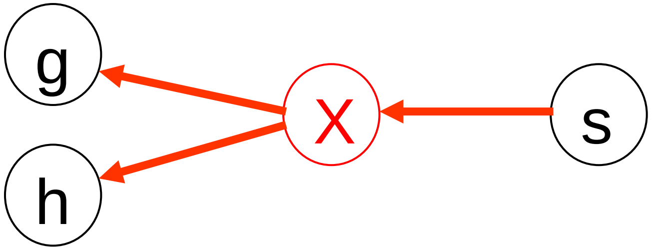


G: *caused(g, s)* ∧ *caused(h, s).*

- Given the abducibles {*connected(_,_)*}, SOLAR generates a hypothesis **H:**

∃*X.* (*connected(g, X)* ∧ *connected(h, X)*

∧ *connected(X, s)*).

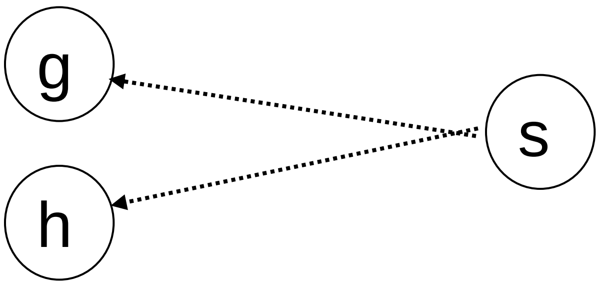


- Variable *X* represents a newly introduced node, which corresponds to **predicate invention** (or **object invention**) in induction.

Representing different structures

B: $\leftarrow$ *connected(g, s).*
$\leftarrow$ *connected(h, s).*

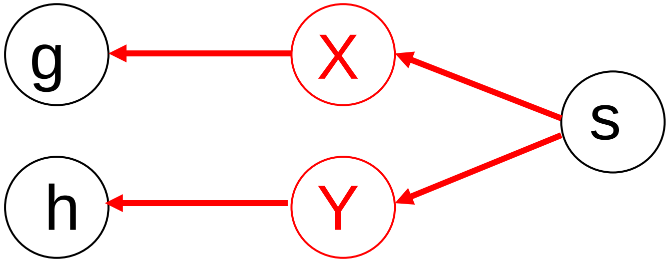
G: *caused(g, s).*
caused(h, s).



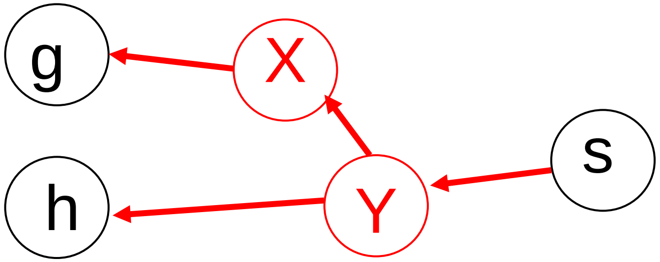
Abducibles: {*connected(_,_)*}.

H with 2 intermediate nodes:

$\exists X \exists Y.\ (\ connected(g, X) \land connected(h, Y) \land connected(X, s) \land connected(Y, s)\ ).$



$\exists X \exists Y.\ (\ connected(g, X) \land connected(h, Y) \land connected(X, Y) \land connected(Y, s)\ ).$



Furukawa’s knack discovery [Inoue *et al.*, ILP’09]

B: connected(inc_sound, bow_close_to_the_bridge).
connected(bow_close_to_the_bridge, stable_bow_movement) ∨
connected(bow_close_to_the_bridge, smooth_bow_direction_change).
connected(smooth_bow_direction_change, flexible_wrist).
← connected(inc_sound, keep_arm_close).
← connected(stable_bow_movement, keep_arm_close).
← connected(smooth_bow_direction_change, keep_arm_close).

G: caused(inc_sound, keep_arm_close).

- SOLAR generates 52 hypotheses when the maximum search depth is 15 and the maximum length of produced clauses is 5. One of them is:

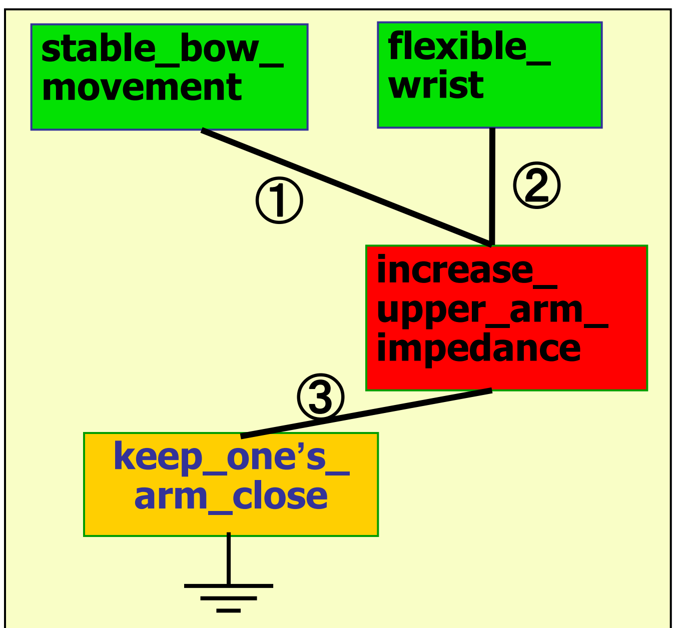
∃X. (connected(stable_bow_movement, X)
∧ connected(flexible_wrist, X)
∧ connected(X, keep_arm_close)).

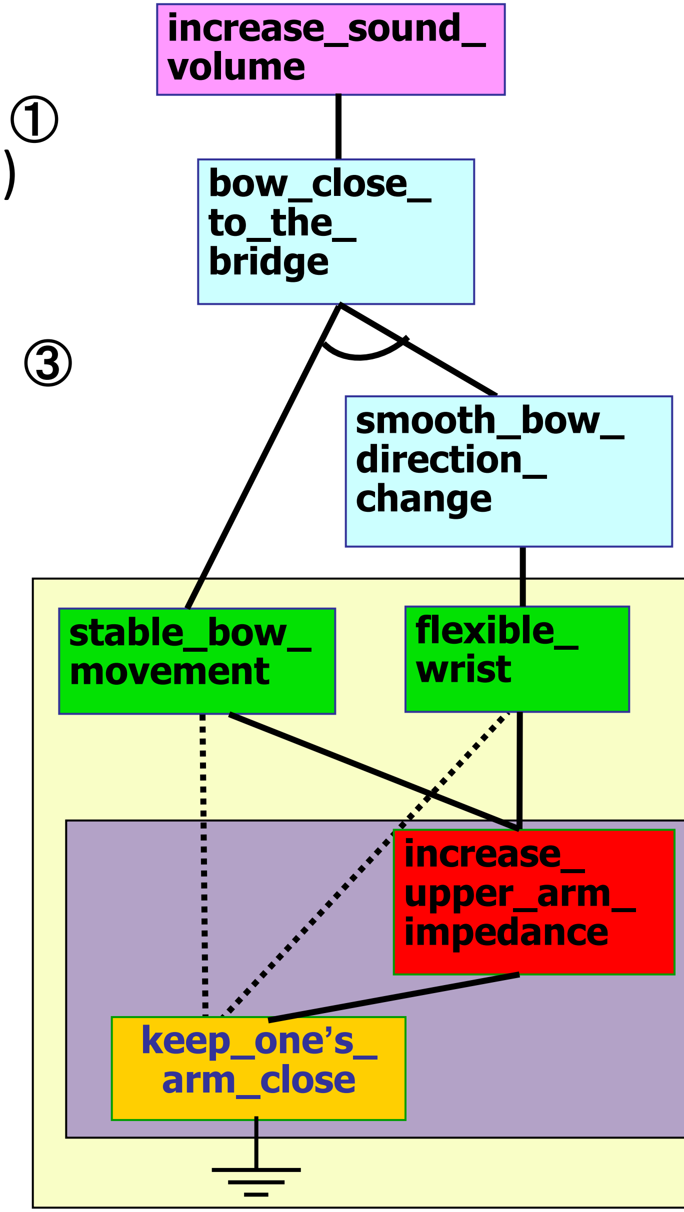
The obtained hypothesis

H: ∃X. (connected(stable_bow_movement, X) ①

∧ connected(flexible_wrist, X) ②

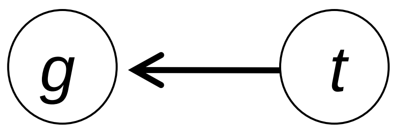
∧ connected(X, keep_arm_close)). ③



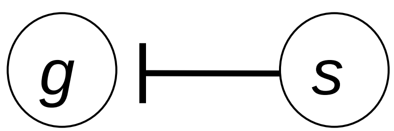


Networks with positive and negative causal links [Inoue, Doncescu & Nabeshima, ILP'10]

- Consider networks with both positive and negative causal effects.
- In biology, such networks appear in gene regulatory/transcription systems, signaling networks, and metabolic pathways.
- Two types of direct causal relations: **triggered** and **inhibited**.
- ***triggered(g, t)*** : a positive direct cause (*t* is a trigger of *g*)



  in a causal graph, whose meaning is ($g \Leftarrow t$) in the object level, where $\Leftarrow$ means that the causation appears *if it is not prevented*.
- ***inhibited(g, s)*** : a negative direct cause (*s* is an *inhibitor* of *g*)



  in a causal graph, whose meaning is ($\neg g \Leftarrow s$) in the object level.

Alternating axioms for causality

- **Causal chains** have two kinds too:
  1. **promoted(X,Y)**: X is *positively caused* by Y.
  2. **suppressed(X,Y)**: X is *negatively caused* by Y.

caused(X,Y) ← connected(X,Y).

caused(X,Y) ← connected(X,Z)∧caused(Z,Y).

promoted(X, Y) ← triggered(X, Y).

promoted(X, Y) ← triggered(X,Z) ∧ promoted(Z, Y).

promoted(X, Y) ← inhibited(X,Z) ∧ suppressed(Z, Y).

suppressed(X, Y) ← inhibited(X, Y).

suppressed(X, Y) ← inhibited(X,Z) ∧ promoted(Z, Y).

suppressed(X, Y) ← triggered(X,Z) ∧ suppressed(Z, Y).

← promoted(X, Y) ∧ suppressed(X,Y).

Monotonic property

- Meta-level abduction is defined for an observation

  promoted(g, s) or *suppressed(g, s)*

  with the abducibles

  Γ = { *triggered(_,_), inhibited(_,_)* }.
- Given positive and negative observations, both positive and negative direct causes are abduced and new nodes are produced when necessary.

- **Proposition:** *For any suppression (resp. promotion) for g from s, there is a causal chain P from s to g such that there exist an odd number of (resp. 0 or an even number of) direct inhibitions in P.*

Axioms with defaults

- Causal chains should have *nonmonotonic* effects.

$promoted(X, Y) \leftarrow triggered(X, Y) \wedge no\_inhibitor(X).$

$promoted(X, Y) \leftarrow triggered(X,Z) \wedge no\_inhibitor(X) \wedge promoted(Z, Y).$

$promoted(X, Y) \leftarrow inhibited(X,Z) \wedge suppressed(Z, Y).$

$suppressed(X, Y) \leftarrow inhibited(X, Y).$

$suppressed(X, Y) \leftarrow inhibited(X,Z) \wedge promoted(Z, Y).$

$suppressed(X, Y) \leftarrow triggered(X,Z) \wedge no\_inhibitor(X) \wedge suppressed(Z, Y).$

$\leftarrow promoted(X, Y) \wedge suppressed(X,Y).$

no_inhibitor(_) : treated as a *default*, which can be assumed during inference unless contradiction occurs.

Abduction with defaults

- For default assumptions of the form *no_inhibitor(_), their negations* are skipped in SOLAR by putting them in the production field.
- Membership of a clause *C* in an extension of a default theory is guaranteed for each obtained consequence of the form

  $C \leftarrow no\_inhibitor(t1) \wedge no\_inhibitor(t2) \wedge \cdots$

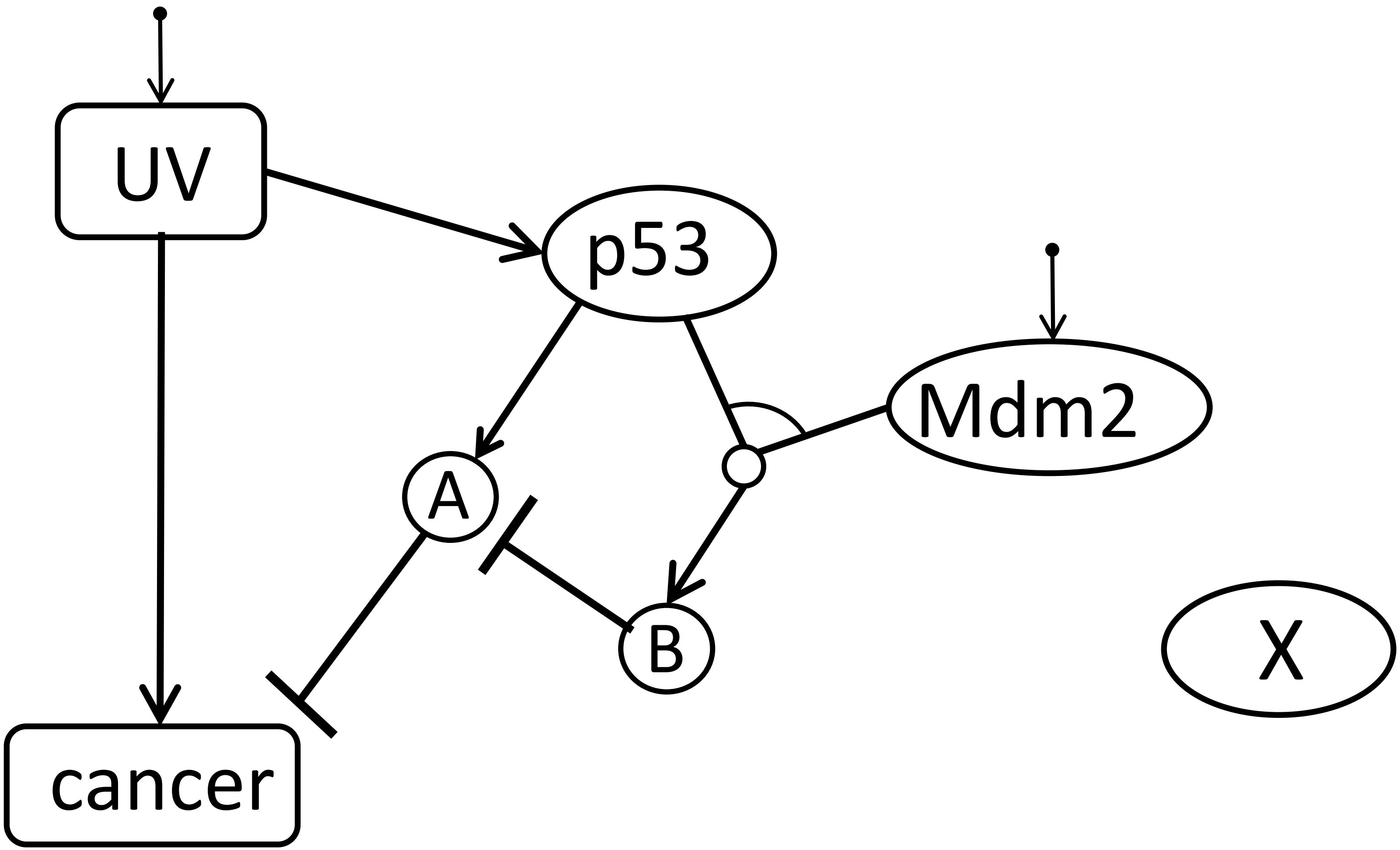
  [Inoue *et al*., 2004, 2006].

Correspondence between object-level inference and meta-level consequence finding

object-level inference	top clause in SOLAR *	production field
proving rules	$\neg caused(g, s)$	none
abducing facts	$\neg caused(g,X) \vee ans(X)$	$ans(\_)$
predicting facts	$\neg caused(X, s) \vee ans(X)$	$ans(\_)$
predicting rules	none	$promoted(\_,\_)$, $suppressed(\_,\_)$
abducing rules	$\neg caused(g, s)$	$\neg triggered(\_,\_)$, $\neg inhibited(\_,\_)$
abducing rules and facts	$\neg caused(g,X) \vee \neg abd(X)$	$\neg triggered(\_,\_)$, $\neg inhibited(\_,\_)$, $ans(\_)$
predicting conditional facts	$\neg caused(X, s) \vee ans(X)$	$\neg triggered(\_,\_)$, $\neg inhibited(\_,\_)$, $ans(\_)$
predicting conditional rules	none	$\neg triggered(\_,\_)$, $\neg inhibited(\_,\_)$, $promoted(\_,\_)$, $suppressed(\_,\_)$

* $\neg caused(X,Y)$ is instantiated by either $\neg promoted(X,Y)$ or $\neg suppressed(X,Y)$.

p53 signal network (Tran & Baral, 2009)



Meta-level representation for p53 signal network

triggered(cancer, uv),

triggered(p53, uv),

inhibited(cancer, a),

triggered(a, p53),

inhibited(a, b),

jointly_triggered(b, p53, mdm2),

jointly_triggered(X, Y,Z) ≡ (triggered(X, Y) ∨ triggered(X,Z)).

Goal and abducibles for p53 signal network

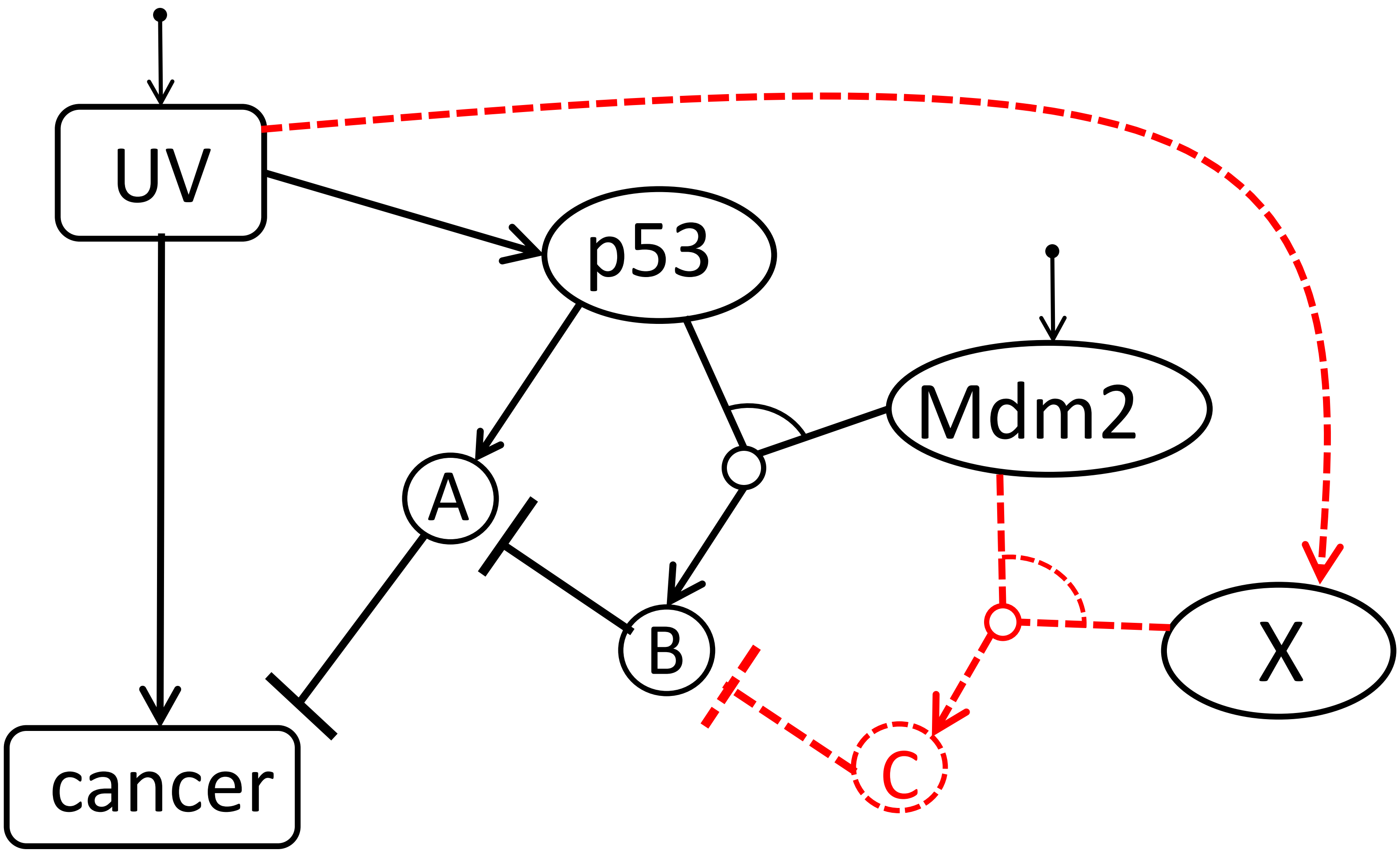
- Consider a tumor suppressor gene X such that mutants of X are highly susceptible to cancer. Suppose exposure of the cell to high level UV does not lead to cancer, given that the initial concentration of Mdm2 is high. These initial conditions are represented as

$$source(uv) \;\wedge\; source(mdm2),$$

i.e., both UV and Mdm2 can be abduced whenever necessary.

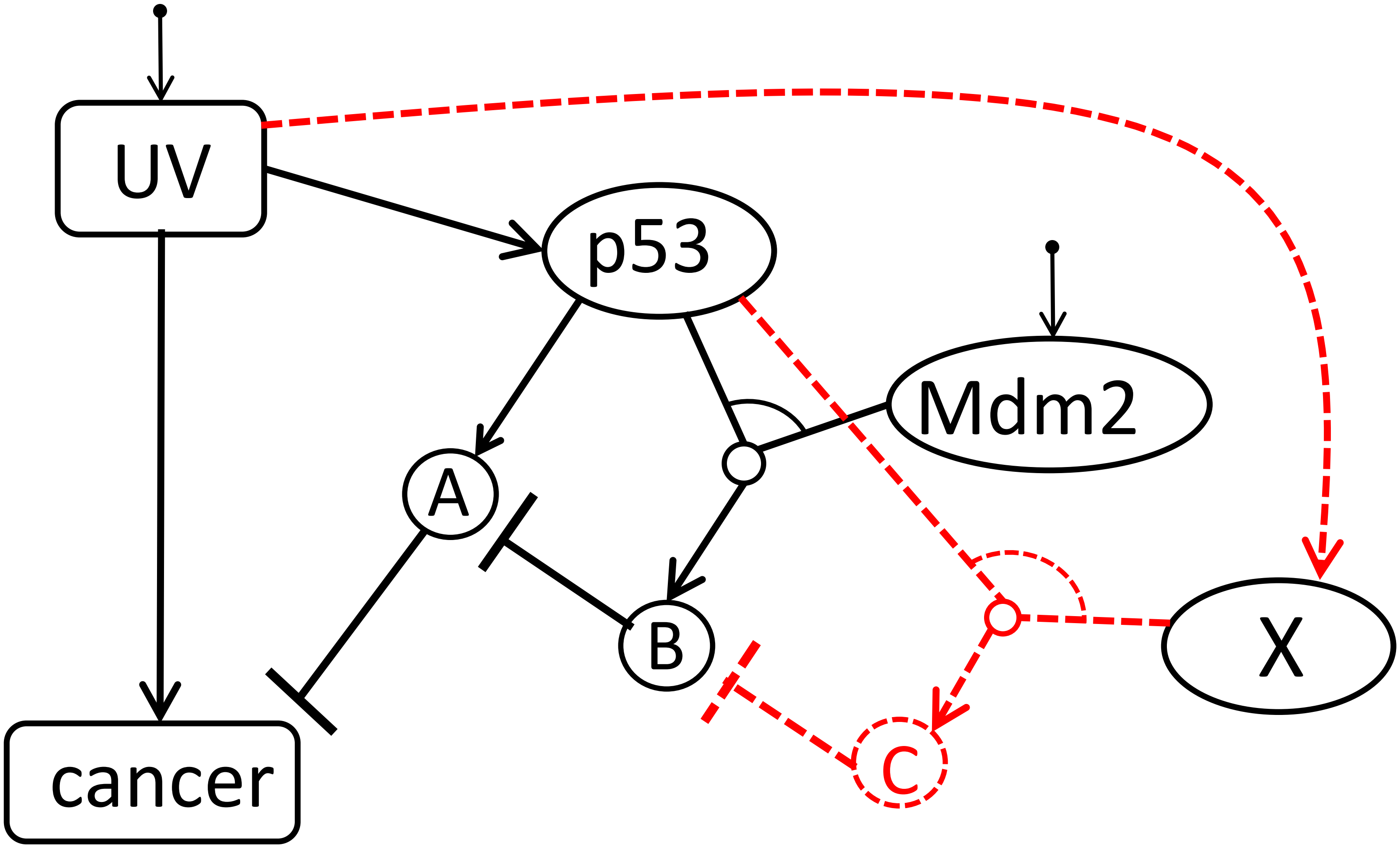
- **Objective**: hypothesize about the possible influences of X on the p53 pathway, explaining how the cell can avoid cancer.
- **Goal**: $\exists S\ (suppressed(cancer, S) \wedge source(S))$
- **Abducibles**: $\Gamma = \{triggered(\_,\_), inhibited(\_,\_), jointly\_triggered(\_,\_,x)\}$
- **Top clause**: $(\neg suppressed(cancer, S) \vee \neg source(S) \vee ans(S))$
- **Production field**: $\{\neg L \mid L \in \Gamma\} \cup \{ ans(\_), \neg no\_inhibitor(\_) \}$
- SOLAR produces 24 minimal hypotheses in 8 seconds.

Hypothesis I



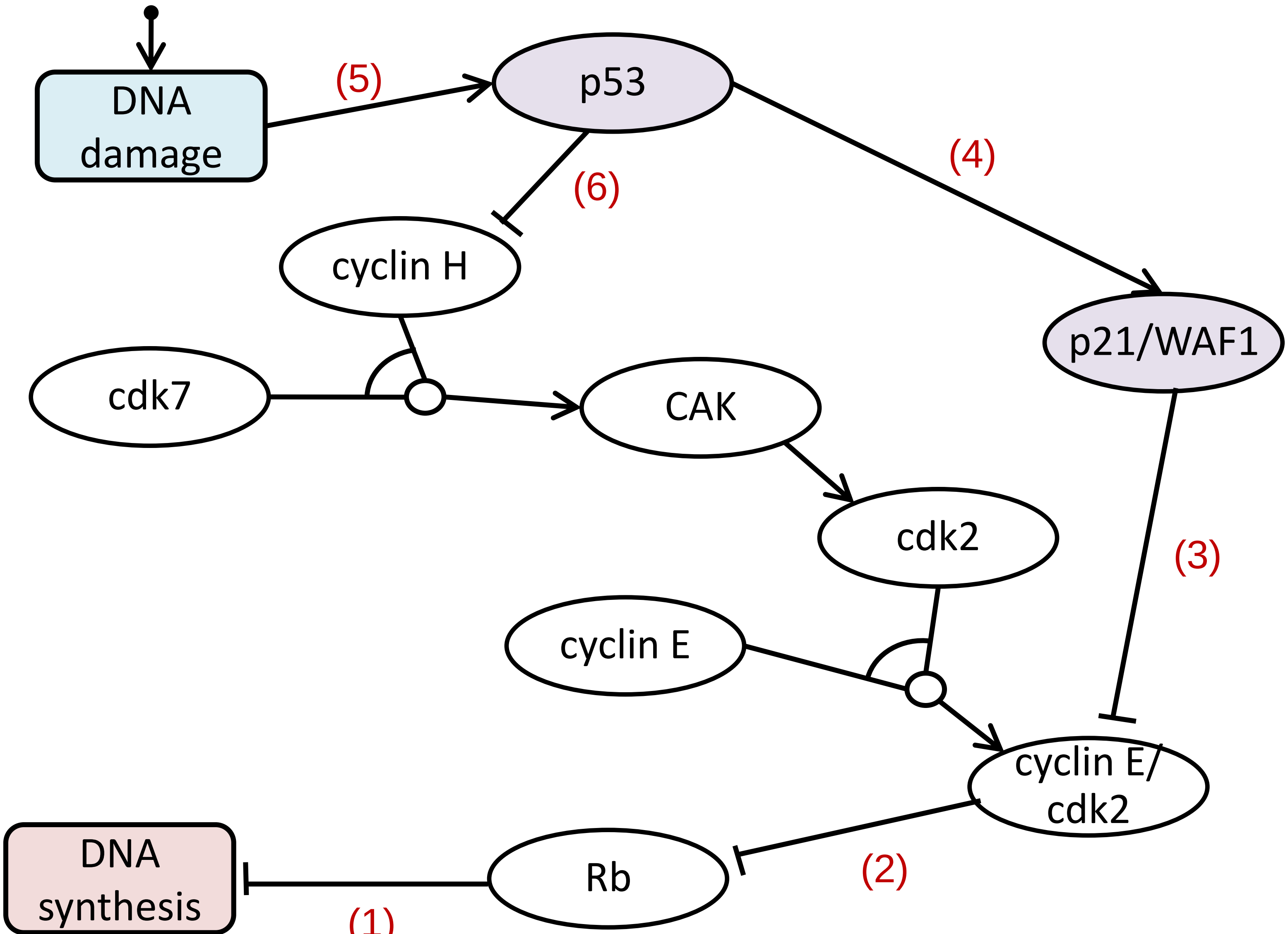
triggered(x, uv) $\wedge$ $\exists Y$ *(jointly_triggered(Y, mdm2, x)* $\wedge$ *inhibited(b, Y))*

Hypothesis II



triggered(x, uv) ∧ ∃*Y* (*jointly_triggered(Y, p53, x)*∧*inhibited(b, Y)*)

Cyclin-dependent kinases (Schneider *et al.*, 2002)



CDK link recoveries (2010.07)

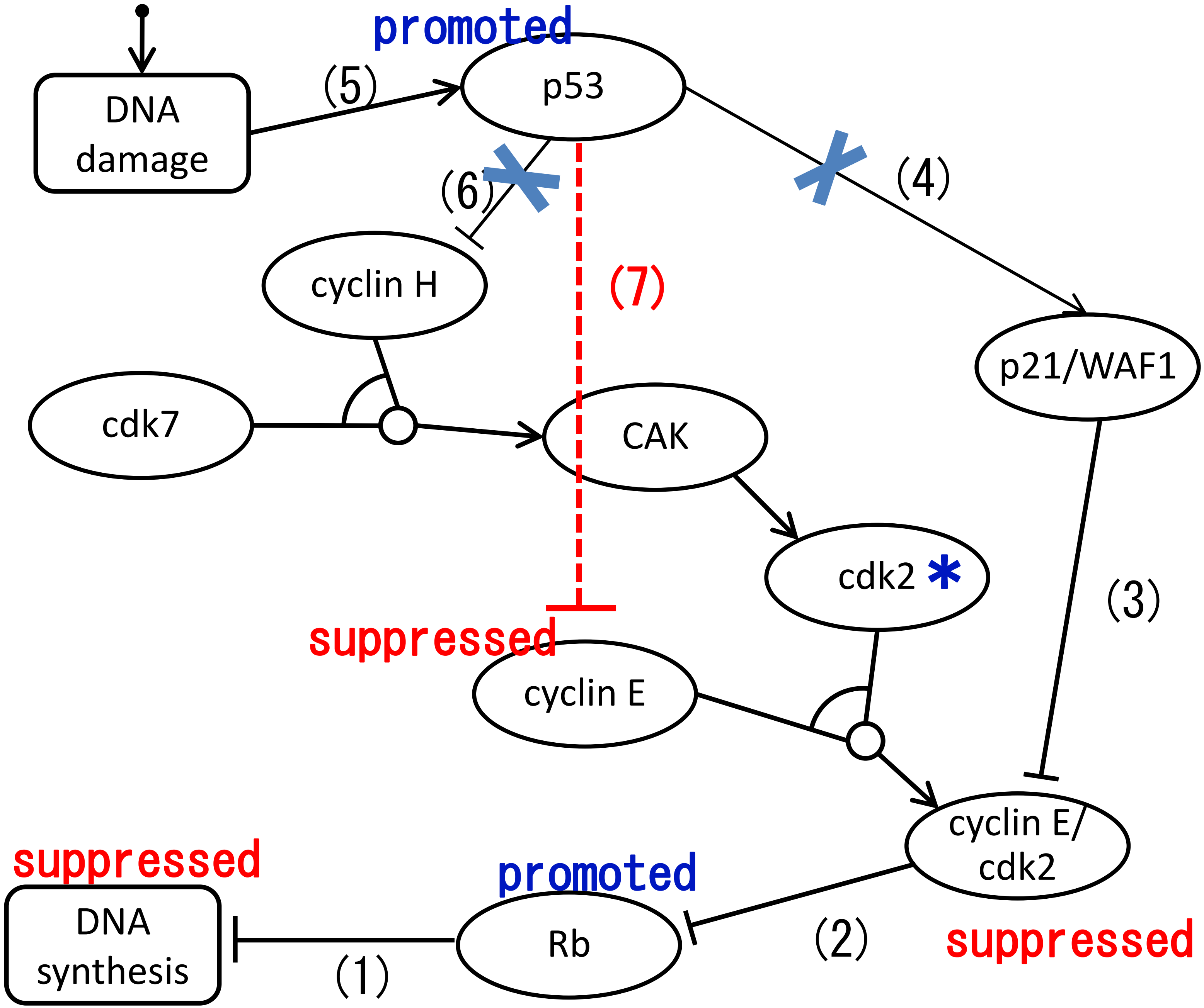
Environment: Mac mini, Core 2 Duo 1.83GHz, 2GB RAM

Carc Computation (**All Nogoods**)

Removed Links	(1)		(1)(2)		(1)(3)		(2)(4)		(4)(6)		(1)(2)(3)(4)(5)	
Depth	Carcs	Time [sec]	Carcs	Time [sec]	Carcs	Time [sec]	Carcs	Time [sec]	Carcs	Time [sec]	Carcs	Time [sec]
3	14	2.3	21	2.2	20	2.1	24	2.1	21	2.0	22	1.9
4	19	4.4	36	4.4	37	4.7	46	6.6	48	4.7	80	4.5
5	19	6.9	36	6.8	39	6.6	50	7.8	56	7.6	202	8.8
6	19	9.3	36	13.6	39	12.0	50	17.1	56	14.7	226	47.1
7					39	31.2	50	44.3	56	44.9	226	284.4
8											226	1655.9

NewCarc Computation (**All Hypotheses**)

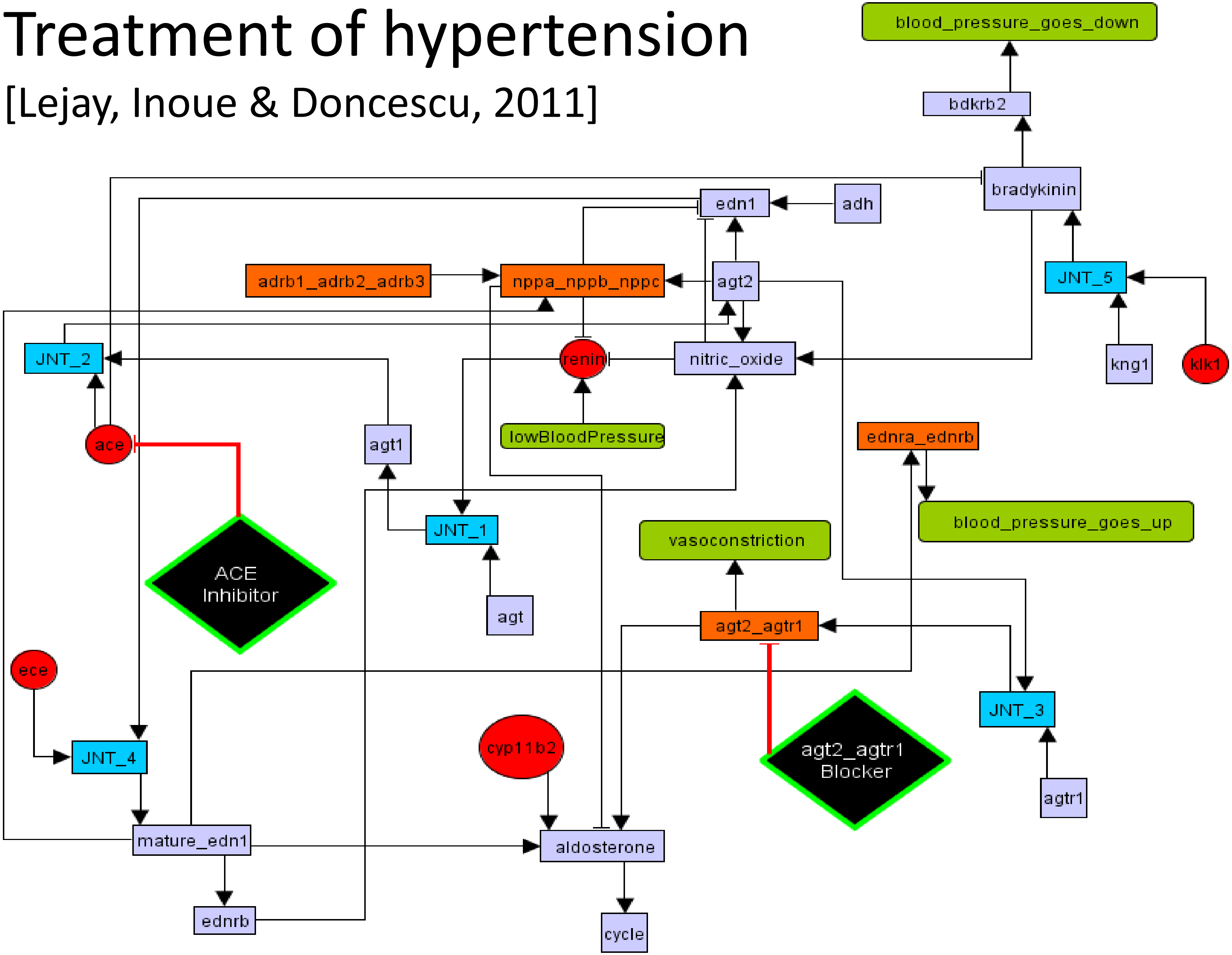
Removed Links	(1)		(1)(2)		(1)(3)		(2)(4)		(4)(6)		(1)(2)(3)(4)(5)	
Depth	New Carcs	Time [sec]	New Carcs	Time [sec]	New Carcs	Time [sec]	New Carcs	Time [sec]	New Carcs	Time [sec]	New Carcs	Time [sec]
3	1	0.7	1	0.7	1	0.7	1	0.8	1	0.8	1	2.1
4	2	0.7	3	0.7	3	0.8	4	0.8	5	0.8	3	2.0
5	3	0.9	4	1.1	5	1.1	8	1.3	6	1.4	7	2.3
6	3	1.5	4	1.7	6	1.5	11	2.1	8	2.2	25	3.5
7	4	1.8	5	2.5	7	2.0	12	3.1	8	3.3	37	5.2
8	4	3.0	5	3.6	7	2.6	12	5.6	8	4.4	37	6.1
9	4	2.3	5	3.9	7	3.2	12	5.2			37	8.6
Recoverd Links	(1)		(1g)(2g)		(1)(3)		(2)(4)		(4)		(1g)(2g)(3g)(4)(5)	



promoted
DNA damage
(5)
p53
(6)
(4)
(7)
cyclin H
p21/WAF1
cdk7
CAK
cdk2 *
(3)
suppressed
cyclin E
cyclin E/ cdk2
suppressed
promoted
DNA synthesis
Rb
(1)
(2)
suppressed

Treatment of hypertension

[Lejay, Inoue & Doncescu, 2011]



Problem Solving with Meta-level Abduction

- Consists of:
  1. design of meta-level axioms,
  2. representation of domain knowledge at the meta level,
  3. restriction of the search space to treat large knowledge.
- The task (2) is tractable.
- The task (1) is important. But other axiomatizations are considerable, e.g., introduction of time, modality, majority logic.
- The task (3) can be realized by introducing more constraints. Automation of constraint generation is future work.
- Hypothesis evaluation/ranking is also important, c.f. (Inoue *et al*., IJCAI-09), (Gat-Viks & Shamir, 2002).