Database repair and dynamic logic

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Outline

1. Motivation: repair via more informative integrity constraints
2. Active Integrity Constraints: postulates
3. Active Integrity Constraints: revisiting the existing semantics
4. ECA constraints
5. An analysis in dynamic logic
6. From AICs to active TBoxes: a sketch
7. Conclusion

Violations of integrity constraints

- ideally: $\mathcal{D} \models \mathbf{IC}$
- but $\mathcal{D} \not\models \mathbf{IC}$ often happens

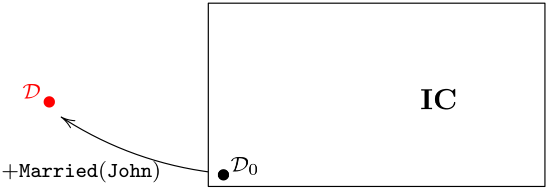
$$\mathbf{IC} = (\forall x)[\mathtt{Bachelor}(x) \wedge \mathtt{Married}(x) \rightarrow \bot]$$

$$\mathcal{D}_0 = \{\mathtt{Bachelor}(\mathtt{John})\}$$

$$\Downarrow \ +\mathtt{Married}(\mathtt{John})$$

$$\mathcal{D} = \{\mathtt{Bachelor}(\mathtt{John}), \mathtt{Married}(\mathtt{John})\}$$

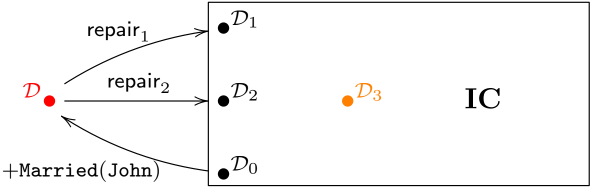
Repairs



Two solutions

1. make $\mathcal{D}$ consistent with $\mathbf{IC}$
   - repair ('data cleaning')
2. live with inconsistent $\mathcal{D}$
   - consistent answer to a query = holds in all possible repairs
   - hypothetical repair

Repairing violations

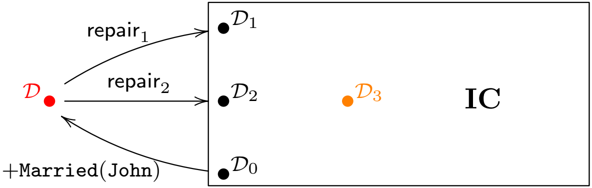


possible repairs of $\mathcal{D} = \{\texttt{Bachelor}(\texttt{John}), \texttt{Married}(\texttt{John})\}$:

$$\mathcal{D}_1 = \{\texttt{Married}(\texttt{John})\}$$
$$\mathcal{D}_2 = \{\texttt{Bachelor}(\texttt{John})\}$$
$$\mathcal{D}_3 = \{\texttt{Bachelor}(\texttt{John}), \texttt{Bachelor}(\texttt{Charles})\}$$
$$\dots$$

- all do the job: $\mathcal{D}_i \models \mathbf{IC}$
  - ... but there are too many
  - ... and some are not intended

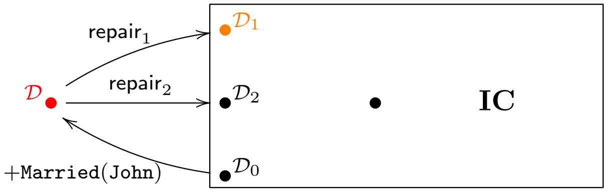
Repairs: minimal change



Minimal repair = a $\mathcal{D}'$ *closest* to $\mathcal{D}$ such that $\mathcal{D}' \models \textbf{IC}$

- intuition: $\mathcal{D}_3$ further away than $\mathcal{D}_1$ and $\mathcal{D}_2$
- definition of closeness?
  - symmetric difference
    - cf. Possible Models Approach PMA [Winslett, AAAI 1988]
    - PMA repairs $\Longrightarrow$ produce PMA updates
  - Hamming distance [Lopatenko&Bertossi, DEXA 2006]

Repairs: minimal change is not enough



- PMA repairs of $\mathcal{D} = \{\texttt{Bachelor}(\texttt{John}), \texttt{Married}(\texttt{John})\}$:

$$\mathcal{D}_1 = \{\texttt{Bachelor}(\texttt{John})\}$$
$$\mathcal{D}_2 = \{\texttt{Married}(\texttt{John})\}$$

  - both closest to $\mathcal{D}$ (for PMA and Hamming distance)
  - but $\mathcal{D}_1$ is unintended
- can we do better by making **IC** more informative?

Active integrity constraints [Flesca et al., PPDP 2004]

"if *condition* holds then do *action*"

- active IC = negation of static IC + update actions

  Static : $(\forall x)[\texttt{Bachelor}(x) \land \texttt{Married}(x) \rightarrow \bot]$

  Active : $(\forall x)[\texttt{Bachelor}(x) \land \texttt{Married}(x), \{-\texttt{Bachelor}(x)\}]$

- intuitions:
  - *"specify for each constraint the actions to be performed to satisfy it"* [Flesca et al., PPDP 2004]
  - *"preferred basic actions to repair [a constraint], if it is violated"* [Caroprese&Truszczynski, TPLP 2011]
- several declarative semantics

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  - *"preferred basic actions to repair [a constraint], if it is violated"* [Caroprese&Truszczynski, TPLP 2011]
- several declarative semantics
- sometimes still not enough information
  - which AIC for $\mathtt{emp}_{e,d_1} \wedge \mathtt{emp}_{e,d_2} \rightarrow \bot$?

Event-Condition-Action (ECA) rules [Ceri&Widow, 1994]

"if *event* occurs and *condition* holds then trigger *action*"

- now we can implement priority to the input:
  - if $+\mathtt{emp}_{e,d_1}$ occurs and $\mathtt{emp}_{e,d_1} \wedge \mathtt{emp}_{e,d_2}$ holds then $-\mathtt{emp}_{e,d_2}$
  - if $+\mathtt{emp}_{e,d_2}$ occurs and $\mathtt{emp}_{e,d_1} \wedge \mathtt{emp}_{e,d_2}$ holds then $-\mathtt{emp}_{e,d_1}$
- active database = database + set of ECA rules
  - huge literature [Ceri et al., ACM TDS 1994; Widom&Ceri, 1996; Chomicki&Marcinkowski, IC 2005,...]
- problem: chaining repairs may not terminate
- problem: no declarative semantics

  "lack of declarative semantics makes it difficult to understand the behavior of multiple ECAs acting together and to evaluate rule-processing algorithms in a principled way" [Cruz Filipe, 2016]

Aims of talk

1. revisit existing AIC semantics
   - rationality postulates (inspired by belief revision literature)
2. generalise to ECA rules [Herzig et al., FoIKS 2022]
   - analysis in dynamic logic
3. sketch transfer to description logics
   - active TBoxes

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3 Active Integrity Constraints: revisiting the existing semantics

4 ECA constraints

5 An analysis in dynamic logic

6 From AICs to active TBoxes: a sketch

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Propositional databases and static integrity constraints

- propositional logic
  - hypothesis: everything is grounded
  - propositional variables $\mathbb{P} = \{p, q \ldots\}$
- databases = sets of propositional variables $\mathcal{D} \subseteq \mathbb{P}$
- update of $\mathcal{D}$ by a set of update actions $A = \{-p, +q, \ldots\}$:

$$\mathcal{D} \circ A = \big(\mathcal{D} \setminus \{p : -p \in A\}\big) \cup \{q : +q \in A\}$$

- static integrity constraints = set of clauses $\mathbf{IC}$

Active Integrity Constraints: syntax

$$r = \langle \mathbf{C}(r), \mathbf{A}(r) \rangle$$

- $\mathbf{C}(r)$ is a conjunction of literals (the negation of an IC)
- $\mathbf{A}(r)$ is a set of update actions ('repair options')
  - each $\alpha \in \mathbf{A}(r)$ makes some literal of $\mathbf{C}(r)$ false:
    - if $+p \in \mathbf{A}(r)$ then $\neg p \in \mathbf{C}(r)$
    - if $-p \in \mathbf{A}(r)$ then $p \in \mathbf{C}(r)$

- database $\mathcal{D}$ + finite set of AICs $R = \{r_1, \ldots, r_n\}$

$$R_1 = \{\langle \texttt{Bachelor} \land \texttt{Married}, \{-\texttt{Bachelor}\}\rangle\}$$

$$R_2 = \{\langle \texttt{Bachelor} \land \texttt{Married}, \{-\texttt{Bachelor}, -\texttt{Married}\}\rangle\}$$

- static constraints associated to R:
  $\mathbf{IC}(R) = \bigwedge\{\neg\mathbf{C}(r) \ : \ r \in R\}$

Active Integrity Constraints: which semantics?

Various semantics

- repairs *tout court*, alias PMA repairs ($\mathbf{A}(r)$ superfluous)
- founded repairs [Caroprese et al., ICLP 2006]
- justified repairs [Caroprese&Truszczynski, TPLP 2011]
- well-founded repairs [Cruz Felipe et al., TASE 2013]
- dynamic repairs [Feuillade&Herzig, JELIA 2013]
- grounded repairs [Bogaerts&Cruz Felipe, AIJ 2018]
- ...

... and each in several versions

- drop minimality requirement $\Longrightarrow$ weak versions
  - for PMA repairs: makes updates drastic
- minimise exceptions
  - preferred update actions are soft constraints, can be violated
  - if static part of R consistent then repair always exists

Active Integrity Constraints: which intuitions?

Permission vs. obligation

when condition $\mathbf{C}(r)$ is violated:

1. permission that the repair contains some $\alpha \in \mathbf{A}(r)$

   "If $\mathcal{D} \models \mathbf{C}(r)$, then $\mathcal{D}$ is inconsistent. It is allowed to repair this inconsistency by executing one or more of the $\alpha_i \in \mathbf{A}(r)$."
   [Bogaerts&Cruz Felipe, AIJ 2018] (notation adapted)

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   ...but $\mathbf{C}(r)$ might as well be repaired by other AICs

2. obligation that the repair contains some $\alpha \in \mathbf{A}(r)$

   To guarantee that $\mathcal{D} \circ A$ satisfies r, $\mathcal{D} \circ A$ must falsify at least one literal in $\mathbf{C}(r)$. To this end A must contain at least one update action from $\mathbf{A}(r)$."
   [Caroprese&Truszczynski, TPLP 2011] (notation adapted)

Active Integrity Constraints: different intuitions, ctd.

Permission vs. obligation: consequences

when $\mathbf{C}(r)$ is true …

1. 'permission' reading:

$$\langle \mathbf{C}(r), \{+p, +q\}\rangle \text{ equivalent to } \begin{cases} \langle \mathbf{C}(r), \{+p\}\rangle \\ \langle \mathbf{C}(r), \{+q\}\rangle \end{cases}$$

   $\Longrightarrow$ all $\mathbf{A}(r)$ singletons ("R normalised")

2. 'obligation' reading:
   - R cannot be normalised
   - computation more local than 'permission' reading:
     "if $\mathbf{C}(r)$ is true then repair via $\mathbf{A}(r)$ regardless of other AICs"

… but what does "$\mathbf{C}(r)$ is true" mean? Just "$\mathcal{D} \models \mathbf{C}(r)$"?

Active Integrity Constraints: sharpening intuitions by means of abstract examples (1)

Example: one violation, no interaction

$$\mathcal{D} = \emptyset \text{ and } R = \big\{ \langle \neg p \wedge \neg q, \{+p, +q\} \rangle, \\ \langle \neg q \wedge r, \{+q\} \rangle \big\}$$

- PMA repairs are $A_1 = \{+p\}$ and $A_2 = \{+q\}$
- principle:

  if $\mathcal{D} \models \mathbf{C}(r)$ and for all other r',

  $\mathcal{D} \not\models \mathbf{C}(r')$ and r' does not *interact* with r,

  then the repairs are just the update actions in $\mathbf{A}(r)$

Active Integrity Constraints: sharpening intuitions by means of abstract examples (2)

Example: two violations, no interaction

$$\mathcal{D} = \emptyset \text{ and } R = \{\langle \neg p \wedge \neg q, \{+p\}\rangle, \langle \neg p \wedge \neg q, \{+q\}\rangle\ \}$$

- different readings lead to different intuitions
  - 'permission': repairs are $A_1 = \{+p\}$ and $A_2 = \{+q\}$
  - 'obligation': repair is $A = \{+p, +q\}$
    - A is not minimal $\Longrightarrow$ not a PMA repair!
    - active part of R badly designed?

Active Integrity Constraints: sharpening intuitions by means of abstract examples (3)

Example: one violation, with interaction

$$\mathcal{D} = \emptyset \text{ and } R = \big\{\langle \neg p, \{+p\}\rangle, \\ \langle p \wedge \neg q, \{+q\}\rangle\big\}$$

- repair is $A = \{+p, +q\}$
  - $\mathcal{D} \not\models p \wedge \neg q$
  - but $\mathcal{D} \circ \{+p\} \models p \wedge \neg q$!
- hence $\mathcal{D} \not\models \mathbf{C}(r)$ not enough a criterion to trigger an AIC
- in general: membership in A may have to be hypothesised
  - problem: circularity of support (v.i.)

Active Integrity Constraints: sharpening intuitions by means of abstract examples (4)

Example: one violation, with interaction

$$\mathcal{D} = \emptyset \text{ and } R = \{ \langle \neg p \wedge \neg q, \{+p\} \rangle, \langle \neg p \wedge q, \{+p\} \rangle, \langle p \wedge \neg q, \{+q\} \rangle \}$$

- intuitions differ
  1. "circularity of support" $\Longrightarrow$ should have no repair [Caroprese&Truszczynski, TPLP 2011]
  2. we: repair should be $A = \{+p, +q\}$
     reason: identity principle applies to first two AICs
     - disjunction of static parts equivalent to $\neg p$
     - dynamic parts identical

  $\Longrightarrow$ first two AICs should be equivalent to $\langle \neg p, \{+p\} \rangle$

Active Integrity Constraints: summary of intuitions

1. permission reading and obligation reading come with different intuitions
    - obligations more local
        - should lead to a simpler account
    - obligation reading often leads to non-minimal repairs
        - may indicate flawed choices of update actions
2. and a crucial principle: identity
    - cf. revision&update postulates...

The Katsono-Mendelzon (KM) postulates for belief update

$\varphi \diamond \psi =$ update of φ by ψ (φ, ψ: propositional formulas)

(U1) $\varphi \diamond \psi \to \psi$;

(U2) If $\varphi \to \psi$ then $(\varphi \diamond \psi) \leftrightarrow \varphi$;

(U3) $\varphi \diamond \psi \to \bot$ if and only if ($\varphi \to \bot$ or $\psi \to \bot$);

(U4) If $\varphi_1 \leftrightarrow \varphi_2$ and $\psi_1 \leftrightarrow \psi_2$ then $(\varphi_1 \diamond \psi_1) \leftrightarrow (\varphi_2 \diamond \psi_2)$;

(U5) $((\varphi \diamond \psi_1) \wedge \psi_2) \to (\varphi \diamond (\psi_1 \wedge \psi_2))$;

(U6) If $(\varphi \diamond \psi_1) \to \psi_2$ then $(\varphi \diamond (\psi_1 \wedge \psi_2)) \to (\varphi \diamond \psi_1)$;

(U7) If φ is complete then $((\varphi \diamond \psi_1) \wedge (\varphi \diamond \psi_2)) \to (\varphi \diamond (\psi_1 \vee \psi_2))$;

(U8) $((\varphi_1 \vee \varphi_2) \diamond \psi) \leftrightarrow ((\varphi_1 \diamond \psi) \vee (\varphi_2 \diamond \psi))$.

The KM postulates for database repair

R = set of AICs
$\mathbf{IC}(R)$ = static constraints associated to R
$\mathsf{Rep}(\mathcal{D}, R)$ = possible repairs of $\mathcal{D}$ via R

(R1) For every $A \in \mathsf{Rep}(\mathcal{D}, R)$, $\mathcal{D} \circ A \models \mathbf{IC}(R)$;

(R2) If $\mathcal{D} \models \mathbf{IC}(R)$ then $\mathsf{Rep}(\mathcal{D}, R) = \{\emptyset\}$;

(R3) If R is *closed* and $\mathbf{IC}(R)$ is consistent then $\mathsf{Rep}(\mathcal{D}, R) \neq \emptyset$;

(R4) If R_1 and R_2 are *equivalent* then $\mathsf{Rep}(\mathcal{D}, R_1) = \mathsf{Rep}(\mathcal{D}, R_2)$;

(R5) If $A \in \mathsf{Rep}(\mathcal{D}, R_1)$ and $\mathcal{D} \circ A \models \mathbf{C}(R_2)$
then $A \in \mathsf{Rep}(\mathcal{D}, R_1 \cup R_2)$;

(R6) If R_1 is *closed* and $\mathcal{D} \circ A \models \mathbf{C}(R_2)$ for every $A \in \mathsf{Rep}(\mathcal{D}, R_1)$
then $\mathsf{Rep}(\mathcal{D}, R_1 \cup R_2) \subseteq \mathsf{Rep}(\mathcal{D}, R_2)$;

(R7) If $A \in \mathsf{Rep}(\mathcal{D}, R \cup \{\langle \mathbf{C}_1, A_1 \rangle\})$
and $A \in \mathsf{Rep}(\mathcal{D}, R \cup \{\langle \mathbf{C}_2, A_2 \rangle\})$
then $A \in \mathsf{Rep}(\mathcal{D}, R \cup \{\langle \mathbf{C}_1 \cup \mathbf{C}_2, A_1 \cup A_2 \rangle\})$.

Extensionality: when are two sets of AICs equivalent?

Definitions

1. $R \approx_0 R'$ if $R = R'$
2. $R \approx_1 R'$ if $\mathbf{IC}(R) \leftrightarrow \mathbf{IC}(R')$ and
   all AICs have same action set
   (there is an A such that $\mathbf{A}(r) = A$ for every $r \in R \cup R'$)

$$\{\langle \neg p \wedge \neg q, \{+p\}\rangle, \langle \neg p \wedge q, \{+p\}\rangle\} \quad \approx_1 \quad \{\langle \neg p, \{+p\}\rangle\}$$

3. $R \approx_2 R'$ if there are partitions of R and R' with $\approx_1$-equivalent cells
   - for every cell ρ of R there is a cell ρ' of R' such that $\rho \approx_1 \rho'$
   - for every cell ρ' of R' there is a cell ρ of R such that $\rho \approx_1 \rho'$

$$\{\langle p \wedge \neg q, \{+q\}\rangle, \langle \neg p \wedge \neg q, \{+p\}\rangle, \langle \neg p \wedge q, \{+p\}\rangle\} \quad \approx_2 \quad \{\langle p \wedge \neg q, \{+q\}\rangle, \langle \neg p, \{+p\}\rangle\}$$

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Well-Founded Repairs [Bogaerts&Cruz Felipe, AIJ 2018]

Idea

1. choose a violated AIC: an $r \in R$ such that $\mathcal{D} \models \mathbf{C}(r)$
2. update by one of the actions in the active part $\mathbf{A}(r)$
3. iterate until no more violation, avoiding repetitions of assignments

Definition

PMA repair A for $\mathcal{D}$ w.r.t. R is well-founded if $A = \{\alpha_1, \ldots, \alpha_n\}$ (for some ordering) such that for every α_i there is an AIC $r_i \in R$ with

- $\alpha_i \in \mathbf{A}(r_i)$
- $\mathcal{D} \circ \{\alpha_1, \ldots, \alpha_{i-1}\} \models \mathbf{C}(r_i)$ (r_i is violated)

compatible with permission reading and with obligation reading

Founded Repairs [Caroprese et al., ICLP 2006]

Idea

- update actions $\alpha \in A$ should be supported by some active constraint r
  - r would be violated without α

Definition

PMA repair A for $\mathcal{D}$ w.r.t. R is founded if

for every $\alpha \in A$ there is an AIC $r \in R$ such that

- $\alpha \in \mathbf{A}(r)$ and
- $\mathcal{D} \circ (A \setminus \{\alpha\}) \models \mathbf{C}(r)$

permission reading (definition checks that every $\alpha \in A$ is permitted)

Grounded Repairs [Bogaert&Cruz Felipe, AIJ 2018]

Idea

- generalises negative condition of foundedness

$$\mathcal{D} \circ (A \setminus \{\alpha\}) \models \mathbf{C}(r)$$

- hypothesis: all $\mathbf{A}(r)$ are singletons ('all AICs are normal')

Definition

PMA repair A of $\mathcal{D}$ w.r.t. R is grounded if

for every $A' \subset A$ there is a $r \in R$ such that

- $\mathbf{A}(r) \cap (A \setminus A') \neq \emptyset$ and
- $\mathcal{D} \circ A' \models \mathbf{C}(r)$

Properties

- all grounded repairs are well-founded, founded, minimal

Justified repairs [Caroprese&Truszczynski, TPLP 2011]

Definitions

- *non-effect actions* w.r.t. $\mathcal{D}$ and A:

$$\mathtt{neff}_{\mathcal{D}}(A) = \{\alpha : \mathcal{D} \circ \alpha = \mathcal{D} \text{ and } (\mathcal{D} \circ A) \circ \alpha = \mathcal{D} \circ A\}$$

- *non-updatable literals* of r:

$$\mathtt{nup}(r) = \{p \in \mathbf{C}(r) : +p \notin \mathbf{A}(r)\} \cup \{\neg p \in \mathbf{C}(r) : -p \notin \mathbf{A}(r)\}$$

- A is *closed under* R if for each $r \in R$,
  - if $-p \in A$ for every $p \in \mathtt{nup}(r)$ and $+p \in A$ for every $\neg p \in \mathtt{nup}(r)$ (r must be triggered)
  - then $\mathbf{A}(r) \cap A \neq \emptyset$
- A is a *justified action set* if it is a minimal superset of $\mathtt{neff}_{\mathcal{D}}(A)$ closed under R
- PMA repair A of $\mathcal{D}$ w.r.t. R is justified if $A \cup \mathtt{neff}_{\mathcal{D}}(A)$ is a justified action set

Justified repairs

Properties

- obligation reading
- violate identity principle!
    - example [Caroprese&Truszczynski, TPLP 2011]:

$$\mathcal{D} = \emptyset \text{ and } R = \{ \langle \neg p \wedge \neg q, \{+p\} \rangle, \langle \neg p \wedge q, \{+p\} \rangle, \langle p \wedge \neg q, \{+q\} \rangle \}$$

- has no justified repair
- identity principle:

$$R \approx_2 \{\langle \neg p, \{+p\} \rangle, \langle p \wedge \neg q, \{+q\} \rangle\}$$

$$\implies \text{Rep}(\mathcal{D}, R) = \{\{+p, +q\}\}$$

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Event-Condition-Action (ECA) constraints: syntax

$$\kappa = \langle \mathbf{E}(\kappa), \mathbf{C}(\kappa), \mathbf{A}(\kappa) \rangle$$

- $\langle \mathbf{C}(\kappa), \mathbf{A}(\kappa) \rangle$ is an AIC
- $\mathbf{E}(\kappa)$ is a boolean formula built from assignments
  - partial description of last update actions
- database $\mathcal{D}$ + finite sets of ECA constraints $\mathcal{K} = \{\kappa_1, \ldots, \kappa_n\}$

$$\mathcal{K}_{\mathtt{emp}} = \{ \langle +\mathtt{emp}_{e,d_1}, \mathtt{emp}_{e,d_1} \wedge \mathtt{emp}_{e,d_2}, \{-\mathtt{emp}_{e,d_2}\} \rangle, \\ \langle +\mathtt{emp}_{e,d_2}, \mathtt{emp}_{e,d_1} \wedge \mathtt{emp}_{e,d_2}, \{-\mathtt{emp}_{e,d_1}\} \rangle \}$$

- static constraints $\mathbf{IC}(\mathcal{K}) = \bigwedge \{ \neg \mathbf{C}(\kappa) \,:\, \kappa \in \mathcal{K} \}$
  - $\mathcal{D} \models \mathbf{IC}(\mathcal{K})$: all the static constraints hold
  - $\mathcal{D} \not\models \mathbf{IC}(\mathcal{K})$: database has to be repaired

ECA constraints: example

Example (adapted from [Flesca et al., PPDP 2004])

- every manager of a project carried out by a department must be an employee of that department
- if e just became manager of project p or if p was just assigned to d_1 then e should become a member of d_1
- if e has just been removed from d_1 then the project should either be removed from d_1, too, or should get a new manager

$$\mathcal{K} = \mathcal{K}_{\text{emp}} \cup \{ \langle +\mathtt{mgr}_{e,p} \vee +\mathtt{prj}_{p,d_1}, \mathtt{mgr}_{e,p} \wedge \mathtt{prj}_{p,d_1} \wedge \neg\mathtt{emp}_{e,d_1}, \{+\mathtt{emp}_{e,d_1}\}\rangle, \langle -\mathtt{emp}_{e,d_1}, \mathtt{mgr}_{e,p} \wedge \mathtt{prj}_{p,d_1} \wedge \neg\mathtt{emp}_{e,d_1}, \{-\mathtt{mgr}_{e,p}, -\mathtt{prj}_{p,d_1}\}\rangle \}$$

- when last update $+\mathtt{mgr}_{e,p}$ then repair by $\{+\mathtt{emp}_{e,d_1}, -\mathtt{emp}_{e,d_2}\}$

ECA rules: too complicated for a declarative semantics?

- mainly procedural semantics
  - termination problems
- only few declarative semantics
  - logic programming semantics [...]
  - Sitcalc [Bertossi&Pinto, 1999; Kiringa, LICS 2001; Kiringa&Reiter 2003]
- can we import AIC semantics?
  - *"[AIC] formalisms do not allow us to specify triggering events"* [Caroprese&Truszczynski, TPLP 2011]

ECA constraints: models

Adding immediate past events

$$\boxed{\text{model } \Delta = \langle \mathcal{D}, \mathcal{H} \rangle}$$

- $\mathcal{D} \subseteq \mathbb{P}$ database
- $\mathcal{H} \subseteq \{+p : p \in \mathbb{P}\} \cup \{-p : p \in \mathbb{P}\}$
  - most recent update action that brought database into state $\mathcal{D}$
  - if $+p \in \mathcal{H}$ then $p \in \mathcal{D}$
  - if $-p \in \mathcal{H}$ then $p \notin \mathcal{D}$
- semantics
  - $\langle \mathcal{D}, \mathcal{H} \rangle \models p$ if $p \in \mathcal{D}$
  - $\langle \mathcal{D}, \mathcal{H} \rangle \models +p$ if $+p \in \mathcal{H}$
  - $\langle \mathcal{D}, \mathcal{H} \rangle \models -p$ if $-p \in \mathcal{H}$
- import founded and well-founded semantics. . .

Founded ECA repairs

- update action A coherent (no $p \in A$ with $+p, -p \in A$)
- update of history $\mathcal{H}$ by A:

$$\mathcal{H} \circ A = A \cup \{\alpha \in \mathcal{H} \,:\, A \cup \{\alpha\} \text{ is consistent}\}$$

Definition

PMA repair A for $\langle \mathcal{D}, \mathcal{H} \rangle$ w.r.t. $\mathcal{K}$ is founded if for every $\alpha \in A$ there is an ECA rule $\kappa \in \mathcal{K}$ with

- $\alpha \in \mathbf{A}(\kappa)$
- $\mathcal{D} \circ (A \setminus \{\alpha\}) \models \mathbf{C}(\kappa)$
- $\mathcal{H} \circ (A \setminus \{\alpha\}) \models \mathbf{E}(\kappa)$

Founded ECA repairs: example

Example, ctd.

$$\Delta = \langle\{\mathtt{mgr}_{e,p}, \mathtt{prj}_{p,d_1}, \mathtt{emp}_{e,d_2}\}, \{+\mathtt{mgr}_{e,p}\}\rangle$$

$$\mathcal{K} = \mathcal{K}_{\mathtt{emp}} \cup$$

$$\{\, \langle +\mathtt{mgr}_{e,p} \vee +\mathtt{prj}_{p,d_1}, \mathtt{mgr}_{e,p} \wedge \mathtt{prj}_{p,d_1} \wedge \neg\mathtt{emp}_{e,d_1}, \{+\mathtt{emp}_{e,d_1}\}\rangle,$$

$$\langle -\mathtt{emp}_{e,d_1}, \mathtt{mgr}_{e,p} \wedge \mathtt{prj}_{p,d_1} \wedge \neg\mathtt{emp}_{e,d_1}, \{-\mathtt{mgr}_{e,p}, -\mathtt{prj}_{p,d_1}\}\rangle \,\}$$

unique founded ECA repair:

$$A = \{+\mathtt{emp}_{e,d_1}, -\mathtt{emp}_{e,d_2}\}$$

Well-founded ECA repairs

Definition

PMA repair A for $\langle \mathcal{D}, \mathcal{H} \rangle$ w.r.t. $\mathcal{K}$ is well-founded if $A = \{\alpha_1, \ldots, \alpha_n\}$ (for some ordering) such that for every α_i there is an ECA rule $\kappa_i \in \mathcal{K}$ with

- $\alpha_i \in \mathbf{A}(\kappa_i)$
- $\mathcal{D} \circ \{\alpha_1, \ldots, \alpha_{i-1}\} \models \mathbf{C}(\kappa_i)$
- $\mathcal{H} \circ \{\alpha_1\} \circ \ldots \circ \{\alpha_{i-1}\} \models \mathbf{E}(\kappa_i)$

Example, ctd.

well-founded repair of $\langle \{\mathtt{mgr}_{e,p}, \mathtt{prj}_{p,d_1}, \mathtt{emp}_{e,d_2}\}, \{+\mathtt{mgr}_{e,p}\} \rangle$:

$$A = \{+\mathtt{emp}_{e,d_1}, -\mathtt{emp}_{e,d_2}\}$$

can be captured in dynamic logic. . .

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2. Active Integrity Constraints: postulates
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Propositional dynamic logic PDL

[Pratt, 1976; Fischer and Ladner, 1979]

- formulas $\langle\pi\rangle\varphi =$ "there is an execution of π after which φ is true"
- programs $\pi_1;\pi_2$, $\pi_1 \cup \pi_2$, π^*, $\varphi?$
  - capture familiar programming constructions:

    "**if** φ **then** π_1 **else** π_2" and "**while** φ **do** π"
  - atomic programs: abstract (just as propositional variables)

Dynamic Logic of Propositional Assignments DL-PA [Balbiani et al., 2013]

- PDL atomic programs $\Longrightarrow$ *atomic assignments* $+p$, $-p$
- concrete atomic programs:
  - $+p$, $-p$: assignments

Syntax of DL-PA$^{\pm}$

Grammar

$$\varphi ::= p \mid +p \mid -p \mid \neg\varphi \mid \varphi \vee \varphi \mid \langle\pi\rangle\varphi$$
$$\pi ::= A \mid \pi;\pi \mid \pi \cup \pi \mid \pi^* \mid \varphi?$$

where p ranges over $\mathbb{P}$ and A over the set of assignments $\{+p : p \in \mathbb{P}\} \cup \{-p : p \in \mathbb{P}\}$

- $\{+p\}$ is a program: "make p true"
- $+p$ is a formula: "p has just been made true"

Semantics of DL-PA$^{\pm}$

For models $\Delta = \langle \mathcal{D}, \mathcal{H} \rangle$

interpretation of formulas:

$$\begin{aligned}
\Delta &\models p && \text{if} \quad p \in \mathcal{D} \\
\Delta &\models +p && \text{if} \quad +p \in \mathcal{H} \\
\Delta &\models -p && \text{if} \quad -p \in \mathcal{H} \\
\Delta &\models \langle \pi \rangle \varphi && \text{if} \quad \Delta ||\pi|| \Delta' \text{ and } \Delta' \models \varphi \text{ for some } \Delta'
\end{aligned}$$

interpretation of programs:

$$\begin{aligned}
\Delta ||A|| \Delta' &\quad \text{if} \quad A \text{ is consistent and } \Delta' = \langle \mathcal{D} \circ A, \mathcal{H} \circ A \rangle \\
\Delta ||\pi_1 ; \pi_2|| \Delta' &\quad \text{if} \quad \Delta ||\pi_1|| \Delta'' \text{ and } \Delta'' ||\pi_2|| \Delta' \text{ for some } \Delta'' \\
\Delta ||\pi_1 \cup \pi_2|| \Delta' &\quad \text{if} \quad \Delta ||\pi_1|| \Delta' \text{ or } \Delta ||\pi_2|| \Delta' \\
\Delta ||\pi^*|| \Delta' &\quad \text{if} \quad \Delta ||\pi^n|| \Delta' \text{ for some } n \geq 0 \\
\Delta ||\varphi ?|| \Delta' &\quad \text{if} \quad \Delta \models \varphi \text{ and } \Delta' = \Delta
\end{aligned}$$

Properties of DL-PA$^{\pm}$

Semantics

- based on classical valuations
  - no Kripke models needed
- Kleene star can be eliminated (not possible in PDL)

$$\langle \pi^* \rangle \varphi \leftrightarrow \langle \pi^{\leq 2^{\mathsf{card}(\mathbb{P}_\pi)}} \rangle \varphi$$

  - consequence: all dynamic operators can be eliminated

PDL vs. DL-PA$^{\pm}$: complexity of decision problems

	PDL	DL-PA$^{\pm}$
Model checking	PTIME-complete	PSPACE-complete
Satisfiability	EXPTIME-complete	PSPACE-complete

Characterising weak well-founded ECA repairs

- fresh auxiliary propositional variables $\mathsf{D}(\alpha)$: record that assignment α has been executed
- legal repair by assignment α:

$$\mathsf{rep}(\alpha) = \neg\mathsf{D}(\alpha) \land \neg\mathsf{D}(\overline{\alpha}) \land \bigvee_{\kappa\in\mathcal{K}\,:\,\alpha\in\mathbf{A}(\kappa)} (\mathbf{E}(\kappa) \land \mathbf{C}(\kappa))?; \{\alpha, +\mathsf{D}(\alpha)\}$$

- program $-\mathsf{D}(A)$ initialises the auxiliary $\mathsf{D}(\alpha_i)$ and $\mathsf{D}(\overline{\alpha}_i)$ to false

Theorem

The set of assignments $A = \{\alpha_1, \ldots, \alpha_n\}$ is a well-founded weak ECA repair of Δ via $\mathcal{K}$ if and only if the DL-PA$^{\pm}$ *program*

$$\mathsf{rep}^{\mathsf{wwf}}_{\mathcal{K}}(A) = -\mathsf{D}(A); \Big(\bigcup_{\alpha\in A} \mathsf{rep}(\alpha) \Big)^*; \mathbf{IC}(\mathcal{K})?; \bigwedge_{\alpha\in A} \mathsf{D}(\alpha)?$$

is executable at Δ.

Characterising well-founded ECA repairs

- fresh auxiliary propositional variables p': store initial value of p in order to check for minimal change
  - program init(A): initialises all D(α) to false and copies the initial values of p into p'
  - program $\mathtt{undo}(\alpha)$: restores original truth value of the variable assigned in α

Theorem

The set of assignments $A = \{\alpha_1, \ldots, \alpha_n\}$ *is a well-founded ECA repair of* Δ *via* $\mathcal{K}$ *if and only if the* DL-PA$^{\pm}$ *program*

$$\mathsf{rep}^{\mathsf{wf}}_{\mathcal{K}}(A) = \mathsf{init}(A); \Big(\bigcup_{\alpha \in A} \mathsf{rep}(\alpha)\Big)^*; \mathbf{IC}(\mathcal{K})?; \Big(\bigwedge_{\alpha \in A} \mathsf{D}(\alpha)\Big)?;$$

$$\neg \Big\langle \Big(\bigcup_{\alpha \in A} \mathtt{undo}(\alpha)\Big)^+ \Big\rangle \mathbf{IC}(\mathcal{K})?$$

is executable at Δ.

Other decision problems

- founded repairs
- Does there exist a repair of Δ via $\mathcal{K}$?
- Is there a unique repair of Δ via $\mathcal{K}$?
- Does every Δ have a unique repair via $\mathcal{K}$?
- Does every Δ have a repair via $\mathcal{K}$?
- Are $\mathcal{K}_1$ and $\mathcal{K}_2$ equivalent?
  - do they repair any Δ in the same way?
- Can $\mathcal{K}_1$ repair strictly more than $\mathcal{K}_2$?
- May the repair of Δ via $\mathcal{K}$ loop?
  - drop the $\mathsf{D}(\alpha)$ tests from $\mathsf{rep}(\alpha)$
  - check whether $\Delta \models [(\mathsf{urep}_{\mathcal{K}})^*]\langle \mathsf{urep}_{\mathcal{K}} \rangle \top$

$\Longrightarrow$ can all can be expressed in DL-PA$^{\pm}$

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From DBs to description logic KBs

Repairs of inconsistent KBs in the DL literature

- *remove* axioms [Schlobach&Cornet, 2003]
- *weaken* axioms [Troquard et al., 2018]
- main methods: axiom pinpointing, justifications, hitting set, weakening of axioms
- usually no preference between possible repairs considered

Can we import the idea of active constraints?

A simple example

Example TBox

$$\mathcal{T} = \{\mathtt{Father} \sqsubseteq \mathtt{Male} \sqcap \mathtt{Parent}, \\ \mathtt{OnlyChild} \sqsubseteq \forall \mathtt{hasSibling}.\bot\}$$

An ABox inconsistent with $\mathcal{T}$

$$\mathcal{A} = \{\mathtt{John}:\mathtt{Male} \sqcap \mathtt{Father} \sqcap \neg\mathtt{Parent}, \\ \mathtt{Mary}:\mathtt{OnlyChild}, \\ \mathtt{hasSibling}(\mathtt{Mary}, \mathtt{John})\}$$

A simple example

An enhanced TBox extending $\mathcal{T}$

$$\mathtt{a}\mathcal{T}_1 = \{\, \langle \mathtt{Father} \sqsubseteq \mathtt{Male} \sqcap \mathtt{Parent}, \{+\mathtt{Male}, +\mathtt{Parent}\}\rangle, \langle \mathtt{OnlyChild} \sqsubseteq \forall \mathtt{hasSibling}.\bot, \{-\mathtt{OnlyChild}\}\rangle \,\}$$

A repaired ABox consistent with $\mathtt{a}\mathcal{T}$

$$\mathcal{A}_1 = \{\mathtt{John} : \mathtt{Male} \sqcap \mathtt{Father} \sqcap \mathtt{Parent}, \mathtt{Mary} : \neg \mathtt{OnlyChild}, \mathtt{hasSibling}(\mathtt{Mary}, \mathtt{John})\}$$

A simple example

An enhanced TBox extending $\mathcal{T}$

$$\mathtt{a}\mathcal{T}_2 = \{ \langle \mathtt{Father} \sqsubseteq \mathtt{Male} \sqcap \mathtt{Parent}, \{-\mathtt{Father}\}\rangle, \langle \mathtt{OnlyChild} \sqsubseteq \forall \mathtt{hasSibling}.\bot, \{-\mathtt{hasSibling}.\top\}\rangle \}$$

A repaired ABox consistent with a$\mathcal{T}$

$$\mathcal{A}_2 = \{\mathtt{John}:\mathtt{Male} \sqcap \neg\mathtt{Father} \sqcap \neg\mathtt{Parent}, \mathtt{Mary} : \mathtt{OnlyChild}\}$$

Repairs based on active TBoxes: difficulties

Challenges

1. ABoxes have concept constructors & complex concepts
   $\Longrightarrow$ 'atomic' update actions not enough
2. *closed world* semantics vs. *open world* semantics
   $\Longrightarrow$ *satisfiability checking* instead of *model checking*
3. *removing* vs. *forgetting* concepts
   $\Longrightarrow$ choice

Proposals

- [Rantsoudis et al., DL 2017]: syntactic approach
- [Feuillade et al., DL 2018]: semantic approach
  - logic $\mathtt{dyn}\mathcal{ALCO}$
- [Rantsoudis, PhD 2018]

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In summary

- reexamined intuitions behind active integrity constraints
  - permission vs. obligation to choose update action
  - rationality postulates for repair
  - justified repairs violate principle of identity
- generalised two AIC semantics to ECA rules
  - founded & well-founded semantics
- sketched repairs based on active TBoxes

Moreover

- analysis in dynamic logic
  - Kleene star accounts nicely for terminating executions only
  - reasoning about repairs *in the logic*